Cooling Tower Performance Analysis and Visible Air Plume Abatement in Buildings Situated in Temperate Climate Zone.

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Content

Nomenclature

A	Area, m^2
a	surface area per unit volume, m^{-1}
c	Concentration, kg/m^3, or constant
c_p	Specific heat of at constant pressure, J/kgK
D	Diffusion coefficient, m^2/s
DBT	Dry Bulb Temperature
F	Force, N
kgDA/kgM	kg of dry air / kg of moisture
MV	Mass Velocity, kg/m^2s
h	Heat transfer coefficient, W/m^2K
h_d	mass transfer coefficient, m/s
i	Enthalpy, J/kg, or coordinate
j	coordinate
k	Thermal conductivity, W/mK, or turbulent kinetic energy
M	Molecular weight, kg/mole
Me	Merkel Number
Q	Heat transfer rate, W

q	Airflow Rate, m^3/s
T	Temperature, °C
u	Internal energy, J/kg
V	Volume, m^3
w	Humidity ratio, kg water vapor/ kg dry air
WBT	Wet Bulb Temperature
x	Coordinate
y	Coordinate

Greek Symbols

μ	Dynamic viscosity, kg/ms
ν	Kinetic viscosity, m^2/s
η	Non-dimensional coordinate
ξ	Non-dimensional coordinate
ρ	Density, kg/m^3

Dimensionless Groups

Le	Lewis number

Le_f	Lewis factor
Me	Merkel number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
RH	Relative humidity
Sc	Schmidt number
St	Stanton number
St_m	Mass transfer Stanton number
POP	Potential of Plume

Subscripts

a	air
fi	Fill
m	mass transfer
s	saturation
ss	supersaturated
v	Vapor
w	Water

Summary

Visible plume was considered as a nuisance to the public due to health and visual issue especially in urban cities, and so heat coils were installed within cooling tower to carry out visible plume abatement. However, as it would be difficult in building to find heat source and high electricity consumption with heat coil, an alternative approach is required.

Prior of developing a visible plume abatement approach, it was essential to identify the formation of visible plume. With this respect, a sophisticated mathematical model, the Poppe Approach was studied and developed a web-based calculator based on the theory. A real size mechanical cooling tower in China was constructed to carry out a validation test and showed to be very accurate and more accurate than the industrial approach, the Merkel Approach.

Based on this validated Poppe Approach, an artificial environmental chamber was designed and constructed in China, and tests were conducted to identify the visible plume formation. CFD simulations were conducted to compare with the experimental results to validate the CFD simulation itself.

Meanwhile, an alternative visible plume abatement approach was developed, the water shedding approach. The water shedding approach was designed to reduce the hour of visible plume occurrence and also to reduce the severity of visible plume. A building load of a commercial building was used to carry out visible plume abatement evaluation with the water shedding approach. With a Hong Kong climatic data, hours of visible plume would reduce by 38.2% and severity of visible plume was reduced by 40 – 60%.

With the validated CFD simulation and the water shedding approach, CFD simulation was conducted in an urban city environment and with cooling tower operating with and without the use of water shedding approach. It was found that CFD simulation results showed that there was a maximum reduction in temperature of 0.33 ^{o}C and maximum moisture content of 0.0003 kgDA/kgM. In order to bridge the gap between academic and industry, a web-based platform was created that stored information related to cooling tower, as well as the fast calculators (the Poppe

Approach calculator and the visible plume abatement calculator) developed during this research topic. This web-based platform would provide engineer a user friendly tool to carry out evaluation in cooling tower plant design and visible plume abatement evaluation.

Summary of Study

The latitude of Hong Kong, 22°18' is close to the Tropic of Cancer. The climate is humid subtropical; therefore almost all buildings are air conditioned for cooling and dehumidification. When the economy of Hong Kong started to flourish after the Second World War, air conditioning in buildings has been a norm for most buildings. In the beginning, air conditioning system was basically packaged air cooled units. Yet as time passes, commercial buildings were built bigger and taller, heat rejection turned into water cooled. However, Hong Kong has little water resources. The then Colonial Hong Kong Government started to build reservoirs with large capacities to catch and store rain water for use by the citizen and city activities. Unfortunately, a serious of droughts occurred in 1964. The executive measures to control the water consumption included water ration for daily use with water supply for four hours in four days. Control measures relating to building services engineering included prohibition of standing water in firefighting systems and use of water for space cooling purposes. Therefore, heat rejection in buildings was solely air cooled until at the turn of the 20th Century.

In order to resolve the water supply permanently, the Colonial Government made an agreement with the People's Republic of China (PRC) Government for PRC to supply fresh water from Dong Jiang River in Shilong of Dongguan in Guandong Province. The river water was extracted and delivered to Hong Kong via a piping system of approximately 100 km. The Colonial Government built a large dam in Plover Cove forming a large reservoir of 281,124 km^3. Since the supply of portable water from PRC in 1968, the threat of drought was hugely reduced. However, the Government then still did not allow the use of portable water for building cooling purposes.

When Hong Kong was handed over to the PRC in 1997, the Electrical and Mechanical Services Department (EMSD, 2004) of the Hong Kong Government of the Special Administration Region started to plan to relax the prohibition of using portable water for building cooling in a pilot scheme. Since then, many of the air cooled plants changed to water cooled and many were planning for this conversion.

The use of cooling towers creates a number of problems:

1. Historically, the Hong Kong Government was very conscious about portable water wastage. As an executive agent of the Government of HKSAR, EMSD is very concerned about the spillage and carryover of water used in the cooling towers.

2. Cooling tower is notorious for its excellent environment for growth of Legionnella that could lead to Legionnaires' Disease Outbreak. It renders a great danger to all operation and maintenance engineers of buildings who have to work closely to this equipment.

3. Cooling tower is an open-typed equipment in HVAC system. The cooling air brings a great load of fine dust into the narrow and corrugated passages of the cooling fills made by pressed and molded plastic sheets. The static electricity induced by the friction of air over the plastic sheets aggravates the fouling of the sheet surfaces. It reduces the retention of water over the surfaces of the sheets and increases the resistance of the flow path. The former lower the water evaporation and the latter reduces the air flow, which both issues reduce the performances of the cooling tower as the heat transfer effectiveness is reduced and the fan power consumption is increased.

4. In the cool and humid climate, which is very common in sub-tropical climatic regions like Hong Kong, the air plume becomes visible subsequent to the re-condensation of the moisture in the discharged air. In an open air and low occupational density environment, it is an acceptable feature. However, when towers are installed at mid-floors of high rise buildings in Hong Kong or installed at back of house, these visible air-plumes always caused unwanted condensation over windows, and mistaken as smoke from fire.

To problems 1 and 2, EMSD reduced these impacts by imposing strict control over the quality of the tower and mandating compliance to cooling tower operation and maintenance requirements. These legal requirements are regulated through the Code of Practice for Water-cooled Air Conditioning Systems published in 2006. Also, any occurrence of Legionnaires' disease had to be reported to the Department of Health, which can be seen in the example of the name of the building having Legionnaires' disease outbreak was announced through media in July 2011.

To problem 3, unfortunately, it is a misnomer for engineers to believe that cooling tower is a simple piece of equipment that requires little attention compared to other equipment like chillers. Therefore, monitoring censors to the cooling towers were almost absent and routine maintenance was not always professional. Although cooling tower consumes little energy as compared to other equipment in the heat rejection system, a small degradation of the heat transfer means a great loss of efficiency to the chillers.

To problem 4, in a city like Hong Kong where the commercial buildings are also sky scrapers. For cooling towers situated in mid-floors, the visible air plume discharges out of building façade. The hot air plume becomes visible in cool and humid climate. The hot visible plume rises and most of the time the plumes will reattach to the façade due to the Coanda effect. It does not only post a fear to the indoor users as mentioned, but also creates a nuisance by blocking the view. With cooling towers installed in podiums or on the roofs, which is very often found in densely populated estates, the visible air plumes will definitely impose threats to nearby citizens. The air plumes may find its ways into the living areas through opening windows.

Statistics result shows that the number of Legionnaires' Disease outbreak increased since the pilot scheme has started. Also, there were many cases that the higher heat rejection effectiveness by cooling tower is nullified by poor maintenance of the cooling towers.

This study was initiated due to the above situations. The problems deserved a detailed study even though the equipment is simple in design. However, the principles of operation are very complicated because the heat transfer from the condenser water to the cooling air is based on a two phase flow of two media; air and water, liquid and steam. In order to understand the impact of the air plume, whether it be visible or invisible, the transportation of the wet air plume had to be studied. In the course of this study, there was a successful attempt in quick detection of legionella by the Polymerase Chain Reaction method. However, as this study inclined to be more scientific oriented, such study was finally decided not to be included in this thesis.

Thus, the aim of this study was set to study the impact of the visible air plume discharged into the atmosphere. The objectives were set to be:

1. Intensive analysis of the heat transfer mechanisms of the cooling tower.
2. Full scale study of the heat transfer performance and air plume study of the cooling tower.
3. Environmental chamber study of the visible plume formation of the cooling tower air plume.
4. Analysis of practical approach for visible plume abatement purposes in a mechanical cooling tower plant.
5. Comprehensive analysis of the dispersion mechanism of the cooling tower air plume.
6. Development of a management platform for the cooling tower.

Chapter 1 – Introduction

1.1 Hong Kong and Building System

The latitude of Hong Kong, 22°18' is close to the Tropic of Cancer. The climate is humid subtropical; therefore the air-conditioning system in almost all buildings was focused on cooling and dehumidification. When the economy of Hong Kong started to flourish after the Second World War, air conditioning in buildings was a norm for building quality. In the beginning, air conditioning system was basically packaged air cooled units due to the serious drought occurred in the 1960s resulted in the lack of water supply distributed to Hong Kong citizens. However, since the purchase of fresh water and dumping of these water recorded in 2000 (*Chan et al, 2004)*, Hong Kong government has again allowed water to be used for cooling purpose due to its higher efficiency in cooling compared to air

With building air-conditioning system, fresh water cooling usually occupied more space than typical air-cooled system as the former would usually include an additional equipment called the cooling tower. Cooling tower is usually constructed in a form of rectangular block, and a large volume is occupied by a plastic substance called the fill where heat exchange would occur between external air with the fresh water circulating within the system. However, as the cooling tower is opened to the external environment, it creates several issues that may affect the surrounding environment, including health and creating nuisance, with its visible plume (Havey, 2008)

1.2 What is Visible Plume

Visible plume from cooling tower would usually occur in a humid environmental condition as discharge air mixes with the external air, which the discharge air would have temperature decreasing rapidly and reduces the capacity of air in holding moisture (reducing in specific volume in air). As the specific volume of air reduces with the reduction in air temperature, the excessive amount of water would condense. However, since these droplets are small in size, the impact of gravity acted upon the droplets would not be significant, resulting in the small droplets flowing along with the discharge air. With the large flow rate discharging humid air into the environment, much water would be condensed into countless droplets and resulting in the form of visible plume under naked eyes.

Visible plume could create a lot of issues, but mainly the issues are:

- Aesthetics/ Neighbor Relations;
- Safety;
- Permitting; and
- Equipment Performance.

1.3 Issues of Visible Plume

- Aesthetics/ Neighbor Relations

Even though the cooling tower plume is made up of water vapor, the community may perceive it as unwanted or smoke-related issues (Brown & Fletcher, 2003). In the past, one of the high-rise buildings that adopted cooling tower in Hong Kong had an experience with a pedestrian called the fire department as mistaken the visible discharged air as smoke. Furthermore, visible plume is commonly being seen as a nuisance and deemed undesirable especially near residential and commercial area (Havey, 2008)

This could be very serious for the building owners because visible plume would occur very often in Hong Kong as it is a city surrounded by sea; which means the humidity level is usually higher than other inland cities. In 2009, the author calculated that there were a total of 1,288 hours that Relative Humidity (RH) in Hong Kong reached above 90%, of which 501 hours and 320 hours were during spring and winter respectively. It is also during these seasons that cooling tower visible plume was more severe because of the low moisture holding capacity at low atmospheric temperature.

- Health & Safety

There are numerous studies on how cooling tower spread Legionella into the atmosphere that causes the outbreak of Legionnaires' disease. One particular argument is upon the inhalation of small droplets which contained Legionella into the human lungs. Rodgers has carried out a study and showed that a droplet of 1 - 3μm long and 0.3-0.9 μm wide is sufficiently large for a single

Legionella to survive (Rodgers, 1978); and Brin suggests that droplets of 0.5mm (500 μm) in radius could flow along air flow with velocity of 0.5 m/s quite effectively (Brin et al, 2002), and 1.0mm (1,000 μm) along air flow with velocity of 1.0 m/s. Given that moist air may contain Legionella as it is discharged at a high velocity (> 3m/s), there is a high chance for people in near to the tower to inhale these polluted particles and become sick.

In Hong Kong, it was recorded that there was an increase of more than five times in the case of Legionella in 2009 since the year 2000, the year when cooling tower was allowed to be used in the air-conditioning system.

- Permitting

Although the Hong Kong government allowed cooling towers to be used, but the government also published a guide for safe installation of cooling towers to avoid any risk induced by the use of the equipment. When cooling tower discharges moist air into the environment with visible plume, it makes owners of the cooling towers more difficult to obtain the permit as official has great concern upon the safety of the cooling equipment to public health. Knowing that permitting can be a long and costly process, eliminating the visible plume would therefore one of the most effective ways to obtain a permit (EMSD, 2004)

- Equipment Performance

A moist environment is not suitable for building systems as moist air can lead to two issues. The first reason is the corrosion of equipment; the second reason is that short-circuiting may arise on the nearby electrical system. Therefore, by elimination of visible plume would also enhance the status of the nearby equipment and allow a longer service life-span of all equipment near to the towers and reduce cost in maintenance (Lucas, 2009).

1.4 Ways of Visible Plume Elimination

In order to eliminate visible plume, retrofitting of the current system is desired. For example, some towers are installed with heater in order to ensure the temperature of moist air could increase, so that the RH of the moist air exiting the tower will not be high and can reduce the chance of visible plume from happening. Although this approach works to reduce risk of visible plume, there is also an increase in temperature that may cause even worse environmental impact due to more heat accumulation within an urban city. Another approach is set out to reduce visible plume, which is the water shedding approach. This approach lowers the water flow rate across the tower, and thus lowers the rate of water evaporation during the air-water heat exchange process within the fill. This approach is useful as it does not require provision of heat source for heating.

1.5 AIM

The aim of the study was to provide a way to construct a mathematical model that can calculate the conditions where visible plume is likely to occur and to reduce/eliminate visible plume with a comprehensive approach. The comprehensive approach involves validation by computation technique with experimental work, and uses computation technique to predict the impact of visible plume within the urban environment. The developed water shedding approach will be used in this research to identify the reduction in visible plume within an urban environment.

1.6Objectives

Objective 1. Heat Transfer Mechanism of Cooling Towers in order to calculate more accurate visible plume condition

The comprehensive analyses of the heat transfer mechanism of cooling tower are reviewed to identify all available models of analysis, which are the Merkel Approach and the Poppe Approach. The Merkel Approach has been adopted in many cooling tower manufacturers for many years due to its simplicity in calculation; however, as computation technology advanced, a more sophisticated model, the Poppe Approach, can be adopted. The advantage of the Poppe Approach is that it does not make assumptions that are used in the Merkel Approach (Klopper, 2003), and thus greatly contributes to the cooling tower performance evaluation by taking into accounts of the unsaturated, saturated and super-saturated conditions of air, in which this highly precise calculation approach can allow a more representative and representable plume severity analysis to be carried out. In addition, this study allowed for construction of an approach that can be used to model the cooling tower at its best condition, which is further described in Objective 2.

Objective 2. Full Scale Tests in order to validate the sophisticated Poppe Approach with a real mechanical cross-flow cooling tower

The construction of a cooling tower is based on the principle of evaporative heat exchange between warm cooling water and ambient outdoor air. The heat transfer effectiveness of the cooling tower is determined by two non-dimensionless coefficients, which are the Merkel Number and the Louis Number. If these values are given, it is then possible to calculate the water outlet condition, as well as the air condition at discharge point (level of humidity of the plume). However, the calculation approach, the Poppe Approach, is only validated with a natural draft cooling tower; although the principle of heat exchange is the same, but as the structural design differs slightly, the calculation approach may not be the same.

A full scale test was carried out to determine the accuracy of the Poppe Approach for mechanical draft cooling towers. In addition to that, the Poppe Approach was also compared with the Merkel Approach (the standard industrial approach). In this study, it was found that the Poppe Approach was very close to the measurement results, and it was more accurate than the Merkel Approach when comparing the calculated results with respect to enthalpy. In addition, prediction model, which allowed for further development on using the cooling tower model in the operating and maintenance stage of the equipment with respect to duty cycling, fouling control, energy management and visible plume abatement, was constructed to model the cooling tower at its best condition

Objective 3. Environmental Chamber Study of Wet Plume of Cooling Towers in order to understand the real visible plume flow pattern and validate with Computational Fluid Dynamics (CFD) Simulations

Although the use of the Water Shedding Approach can reduce the severity of visible plume; yet the formation of visible plume was not clearly understood. There is existing Computational Fluid Dynamic (CFD) simulation in the industry to simulate the case of visible plume, but these simulations are seldom validated with proper measurement. One reason for this is because the real case scenario of visible plume is very difficult to be identified and hard to carry out experiments on the spread of visible plume. Therefore, an artificial environmental chamber, with the dimension of 2.5m x 6m x 3m in height, is designed to allow for an easier experimental measurement on visible plume formation with a scaled down discharge point of a cooling tower. By providing a humid artificial environment, saturated air discharged into the artificial environment would easily form visible plume. This allows validation between experimental results and CFD simulations, and the validated CFD simulation approaches can then be used in real case scenario within any environmental and topological conditions. This forms a major and original contribution to the study of cooling tower visible plumes.

Objective 4 Alternative Visible Plume Abatement for Cooling Towers

If visible plume is not acceptable when a group of cooling towers are installed in the proximity of residential or commercial areas, plume abatement is necessary. At present, the most common approach is to heat up the moist air to reduce or to eliminate visible plume; yet, this approach is not at all effective due to several design issues.

An alternative approach is developed in the research thesis that does not require a heat source to reduce the discharge air humidity. During the study, it is found that visible plume is very likely to occur during spring and winter times (Refer to Figure 35). During these seasons, not all cooling tower is operational and many towers will remain idle. With this in mind, cooling load can be shared between two or more cooling towers that are available on-site during these seasons, thus reducing the humidity level of discharge air, thus achieving visible plume abatement. The detail of the operating approach shall be discussed in Chapter 6.

Therefore, a unique approach, which would be more time effective, was proposed in setting up procedures for plume abatement. The followings would be the procedures of the alternative visible plume approach：

1. Evaluation of air plume condition under the designed profiles of the cooling load and the annual climatic condition. This was a composite procedure of the cooling tower performance evaluation together with the chiller models and the electronic psychometric chart.
2. Evaluation of the condensation indicator to compute the frequency of visible plume due to condensation.
3. Evaluation of the severity of the visible plume and identify if whether plume abatement would be necessary.
4. Evaluation of the effectiveness of plume abatement options by proposing a unique methodology, the Water Shedding Approach, to reduce the severity of visible plume, or to eliminate the visible plume.

Objective 5. Dispersion Analysis of Cooling Tower Plume in order to understand how visible plume affect an urban city with the use of CFD Simulations

The compactness, or the density, of the urban city is one of the reasons for heat accumulation, and in particular the hot and misty air discharged from the cooling towers. As saturated air condenses, some of the drifts exit the cooling tower may become larger in size or difficult to evaporate into the humidified outdoor environment in close range of the towers. These drifts may be contaminated due to the design natural of the tower (open system), and can lead to spread of bacteria, such as Legionella as it can remain in the drifts at small size. With the CFD simulation validated and the heat transfer model constructed to simulate an accurate discharge air conditions, the dispersion of visible plume within an urban environment could be identified. With this respect, CFD simulation was adopted to simulate the dispersion of visible plume when placed at different location in a generic urban city model, and identified the rate of dispersion under different wind speed. These simulations would help to predict and prevent nuisance (health and visual) imposed on both residents and pedestrian in close proximity.

Objective 6. A Computer Aided Cooling Tower Manager to help the public to understand the risk of visible plume within an urban environment

Although the study carried out from Objectives 1 – 5 is fairly comprehensive from the basic of heat transfer in cooling tower leading to the identification of impact of visible plume discharged into the urban environment. However, this information cannot be easily used in the industry to provide the public with a wider understanding and the impact of visible plume of cooling tower.

With this in mind, a computer aided cooling tower manager was constructed to compile all the research information. The cooling tower manager integrated all the information into an intelligent platform for the purpose of improving building system management. The aim was to ensure research skills are put into practice as it is believed that any engineering research outcomes would be deemed useless if they could not be adopted in practice. In additional, this management platform would increase the public awareness on cooling tower on its potential in spreading disease and causing disruption in plant normal operation. The platform included a comprehensive and illustrative web platform that would provide the basis of model and tool development for proper cooling tower performance evaluation and visible plume dispersion risk prediction.

Overall

All the objectives above correlate with one another, and the relationship between objectives were shown in the diagram below. The path to the left of the diagram (Figure 1) is the validation path, which the thermal model made of the Poppe Approach was validated with a real mechanical cooling tower and compared with a not as sophisticated model, the Merkel Approach. The result showed that the Poppe Approach was more accurate than the latter. Then, the Poppe Approach was used to design an artificial environmental chamber. The chamber was developed based on the Poppe Approach, and the purpose of the model was to determine the shape of visible plume and to validate CFD model based on this artificial environmental chamber.

The path on the right was the empirical path, which was the development of the visible plume abatement approach, the Water Shedding approach, in order to reduce or even to eliminate the plume visibility. This in-depth analysis would allow a thorough evaluation of the operating schedule of cooling tower throughout a year with the most recent yearly local climatic data. In this study, the Hong Kong weather profiles were used to evaluate how much plume could be eliminated during a year.

Both the CFD evaluation and the development of the Water Shedding approach would be useful to identify the risk of visible plume in an urban environment. For example, the potential risk in the spread of Legionella. Ever since cooling towers became more common in building during recent years, statistics based on government's data had shown that the number of Legionnaires' Disease cases recorded have increased quite significantly. Therefore, the analysis for a CFD simulation of visible plume of a cooling tower within an urban environment and visible plume reduction would be very valuable to understand whether visible plume (droplets that may contain Legionella) would reach close to the people within an urban environment.

At last, all the data and many information related to cooling towers were combined and placed into a computer aided internet platform, the cooling tower manager, in order to efficiently share the information to the public and to increase the health awareness and the importance of cooling tower in building. Figure 1 and Table 1 showed the details of the objectives and how each objective related to another.

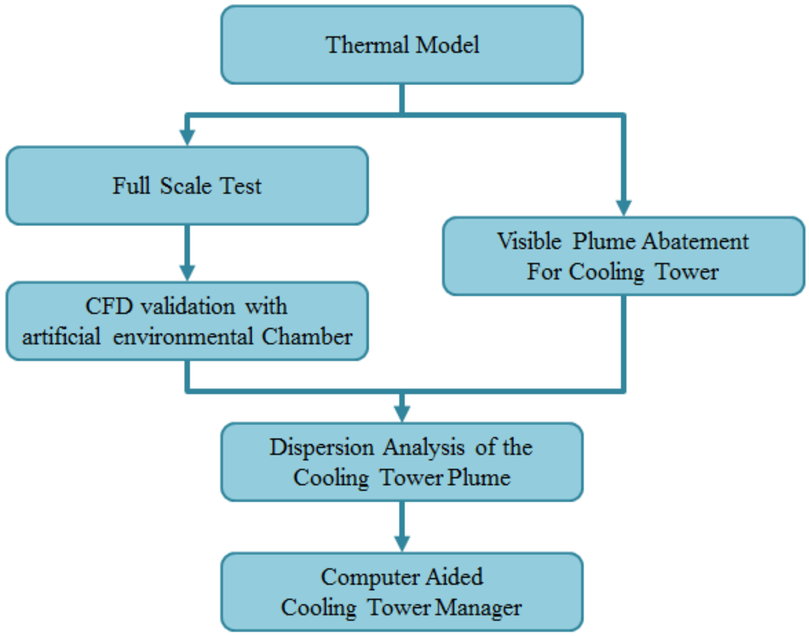


Figure 1 Summary of each objective

Table 1 Summary table of objectives

Objective	**Description**
Objective 1 Thermal Model	Development of a sophisticated calculation tool for cooling tower. The Poppe Approach was adopted to construct a computational model as it was the most accurate, then would be used to compare with the approach used commonly in the industry, the Merkel Approach. Script was used to shorten the calculation time as the iteration process of the Poppe Approach took a long period of time and enhanced the research time when computation power was not as effective as the present compared to when the approach was developed in the early 1900s.
Objective 2 Full Scale Test	Validation of cooling tower mathematical thermal model with a real mechanical cooling tower. Another reason for the full scale test was to identify which approach, the Poppe Approach and the Merkel Approach, was more accurate. This was essential as visible plume abatement in the industry was carried out based on the Merkel Approach. If the Poppe Approach was more accurate with respect to heat transfer process within cooling tower, then a more accurate visible plume abatement strategy could then be developed.
Objective 3 Environmental Chamber	Created visible plume in a controlled environment (Use of thermal model to meet the condition where visible plume would occur) and

Objective	Description
Study with CFD	validated Computational Fluid Dynamic (CFD) simulation by comparing with experimental results. Fluent was used for the CFD simulation as it was an accurate computation program. The k-ε turbulence model was adopted and used the CFD program to identify the plume formation and its severity under different environmental and discharge air condition. However, in order to show that the CFD simulation was accurate, the results must be validated. An artificial environmental chamber with size of 2.5m x 6m x 3mH was designed to validate the CFD simulations by carrying out a case with the same background and discharge air condition as the CFD simulation.
Objective 4 Visible Plume Abatement for Cooling Towers	Introduced a new methodology, differ from the industrial approach, to reduce visible plume severity or to eliminate it. The methodology used was the water shedding approach, which water would be share amongst cooling towers available instead of one to reduce water flowing across each tower to lower the Water to Air ratio of tower. This would result with a lower humidity level of air discharged into the environment.
Objective 5 Dispersion Analysis of the Cooling Tower Plume	Use of CFD simulation to identify visible plume dispersion within a typical urban environment with high building density and compared severity between with and without the proposed new methodology for visible plume abatement. CFD technique with k-ε turbulence model was used (validated with the artificial environmental chamber), and a 3D model of an urban environment was constructed with a cooling tower placed at the middle between two buildings. The calculation was carried out identify the impact of cooling tower discharge under different wind impact when water shedding approach was used and when it was not used.
Objective 6 Computer Aided Cooling Tower Manager	Compilation of all researched information and incorporated into a user-friendly web-based cooling tower manager with the aim to promote advance cooling tower design and management with ease. The aim was to increase the public awareness of the effect of cooling tower with respect to the environmental quality and the health issues it could cause if not taken with serious consideration. The future work will be to launch the website into public and conduct questionnaire to understand how the website can increase the public awareness of cooling tower hazard.

The structure of the thesis is based on the objectives with each objective covered by a chapter. Chapter two introduced subject area and reviewed some of the literature. In addition, the literature was reviewed in each chapter as appropriate.

Chapter 2 – Review of Subject Area

The basic function of a building is to provide the occupants with a comfortable environment either for living and working. Four criteria factors are listed when establishing the standard of Indoor Environmental Comfort (IEQ): humidity level, noise, lighting and air quality. For any system that requires power to operate, including human activities, heat will be generated and has to be rejected to maintain an excellent IEQ level. Inevitably, the Heating, Ventilating and Air-Conditioning (HVAC) system plays an important role in rejecting the considerable amount of building heat load as well as to control a good indoor environmental condition. In America, the last Commercial Buildings Energy Consumption Survey (CBECS) has been carried out by the Department of Energy Information Administration: Department of Energy (EIA DOE) in 1999.
In building, chiller is used to remove heat generated within the building via human activities. There are two types of chillers used often in building; Air-Cooled Chiller (ACC) and Water-Cooled Chiller (WCC). As the names suggested, ACC is to cool the refrigerant cycling the building with air, whereas WCC is to use water for cooling. In general, WCC is more efficient than ACC as the water cooling system depends on the ambient wet bulb temperature whereas air cooling system depends on the ambient dry bulb temperature. The dry bulb temperature is almost always higher than the wet bulb temperature and is highly affected by environmental conditions and seasonal changes. Mendes has elaborated a flexible computational algorithm for performance analysis of HVAC system and showed that WCC was more efficient than ACC when Part Load Ratio (PLR) was less than 60% and required 13% less annual energy consumption in comparison to ACC under the same operating load (Mendes et al, 2008).

Although water is a more effective cooling media, but due to the geographical location, rise in water cost from inflation, environmental considerations, legislation, public health and comfort (Chan et al, 2004, Micheletti, 2006, Steele, 1975, Ricketts & Joseph, 2006, Jameson, 1997), all makes it more difficult to select the most optimum system that gives consideration to efficiency, economy and environmental impact.

2.1 Water Sources, Supply and Storage in Hong Kong

During the early Hong Kong colonial period, clean water supply to citizens of Hong Kong Island started in the 19th Century. Before 1860, water supply in Hong Kong came from rivers and wells. Popular water source locations were indicated by their names such as Waterfall Bay (at the Southern part of Hong Kong Island and is now the popular Wa Fu Estate) and Shui Hang Kau (meaning the exit of a water channel) at the Northern part of Hong Kong Island. There was no sign of its importance as water sources anymore. It is interesting to note that the Colonial Government spent 47 pounds and 4 shillings to sink four wells in the area of Victoria (now the Central District, the administrative and commercial centre of Hong Kong). Hong Kong was underlain by granite and there was little useable ground water. Therefore, the obvious viable solution to meet the demand of growing population was to build reservoirs to collect rain water with catchments. In 1863, the first reservoir in Hong Kong Island, the Pok Fu Lam Reservoir was built. As Kowloon and New Territories became ruled land of the Colonial Government, the first reservoir in Kowloon, the Kowloon Reservoir was built in 1910. In order to cope with the rapid increase of population (flushing from Mainland China) and the fast economic growth after World War II, 14 reservoirs were built by damming valleys and low lands in mountains before 1965. Due to the lack of land within the total area of 1,098 m^2, further reservoirs were built in the sea by damming and draining the sea water. The first one was built at the inlet of the Tolo Harbour with storage of 170 million m^3 and increased to 230 million m^3 in 1973. The largest reservoir at the moment was built at High Island which has a capacity of 281 million m^3 (Chan et al, 2004)

2.1.1 Water Purchasing

According to the 1999 Report by the Hong Kong Legislative Council on a review to ascertain whether there was room for improvement in the planning of the purchase of water from Guangdong Province, one of the major findings was:

"Since 1994, there had been an excess water supply from Guangdong Province mainly because water consumption in Hong Kong had increased at rates lower than those forecast. As supply exceeded demand, the water in the reservoirs often reached a high level, resulting in reservoir overflow whenever there was heavy rainfall. From 1994 to 1998, the overflow quantity was 716 M m^3. The financial implication could amount to HK$1,718 million." (Chan et al, 2004).

"While the 1989 Agreement had included a mechanism to increase the supply of Dongjiang water if necessary, there was no provision for a reduction in water supply if the growth rate of water consumption were to decline in Hong Kong" (Legco, 1999).

Hong Kong has low bargaining power as the land is not effective in collecting natural rain water and is also much less than what is needed for steady supply to meet the demand. Secondly, the Guangdong Authority had already invested heavily in the infrastructure to supply water to Hong Kong and required a guaranteed return for a fixed period on its investment.

2.1.2 Water Wastage – Opportunity for Cooling Towers

While cooling tower was not able to obtain permit for installation in Hong Kong due to the water drought in 1964 and 1967 (Chan et al, 2004), but it became easier since June 2000 when the Electrical Mechanical and Building Services Department (EMSD) issued the Fresh Water Cooling Towers Scheme for Air Conditioning Systems. The following reasons could be the cause for allowing the use of cooling tower in Hong Kong:

- Financial Consideration – huge amount of water dumped into the sea after purchasing from Dongjiang and Hong Kong government was not able to reduce the amount of water purchased based on the contract signed by the Hong Kong government (Legco, 1999).

- Technical Consideration – Water cooled chillers have higher Coefficient of Performance than air-cooled chillers. Based upon a study for a tall building in Hong Kong, the electricity consumption has decreased by 20.4 % after shifting from the use of air-cooled system to water-cooled system. The higher efficiency of the use of water-cooled system is also reflected in the Code of Practice for Energy Efficiency of Building Services Installation published by EMSD where the Coefficient of Performance (COP) of air-cooled chiller of different type could reach between 2.6 – 2.8 while full load while COP water-cooled chiller of different type easily reach between 4.1 – 5.7.

The Fresh Water Cooling Towers Scheme for Air Conditioning System is a 2-year pilot scheme and launched in 6 selected areas where existing water supplies and sewerage network would be adequate to meet the additional demand. The working group comprises members from two government bureau and eight government departments.

The pilot scheme was first launched in 2004 with the aims to (EMSD, 2004):

(a) Promote energy-efficient water-cooled air conditioning systems;

(b) Assess the additional water demand;

(c) Monitor the quantity and quality of bleed-off effluent discharge from the systems;

(d) Monitor the health and environmental effects arising from the systems; and

(e) Collect useful information and data so as to facilitate the territory-wide implementation study of water cooled air conditioning systems.

The construction of cooling tower is relatively simple as compared to other mechanical equipment. However, the heat transfer is more complicated due to its two-phase heat exchange characteristic. Given the tight control on the consideration of design, testing, operation and maintenance of the cooling towers as regulated by the Ordinances, Technical Memorandum and Code of Practice (EMSD, 2004), a thorough study of the cooling tower is necessary.

2.2 Basics of Cooling Towers

2.2.1 Physical Principle of Cooling Tower

The principle of psychrometry is the physical system of gas-vapor mixture, where one or more vapor components may remain at the gaseous phrase while the other components condense. With cooling tower, water vapor in the moist discharged air may condense if mixed with a humid (almost saturated) ambient air. A psychrometric chart is shown in Figure 2, and can be used to show the change of state of water-air mixture within a cooling tower.

The psychrometric chart is constructed by seven properties of water-air mixture, these properties are: dry bulb temperature, wet bulb temperature, atmospheric pressure, RH, moisture content, specific volume and enthalpy. With three of the seven properties available, including the atmospheric pressure, are specified, it is possible to determine the thermal state of the mixture (Shallcross, 1997).

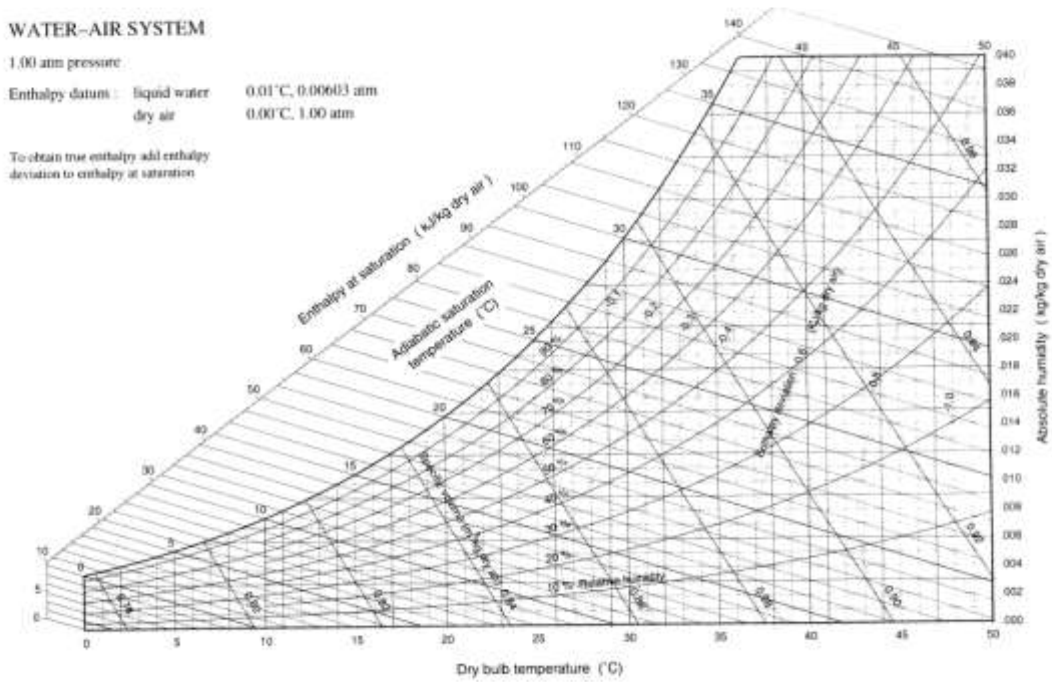


Figure 2 Psychrometric Chart (Shallcross, 1997)

In heat and mass transfer, various processes are possible for water-air mixture. These include the heat transfer in cooling and heating as well as the mass transfer in humidification and dehumidification (Legg, 1991). Within cooling tower, water transfers heat into the air stream, as well as the evaporation effect; therefore, it is common for air to increase in temperature and moisture content. However, it is also possible for both water and air to be cooled when under a very hot and dry atmospheric condition. Figure 3 demonstrates this process by showing the enthalpy transfer in a psychrometric chart.

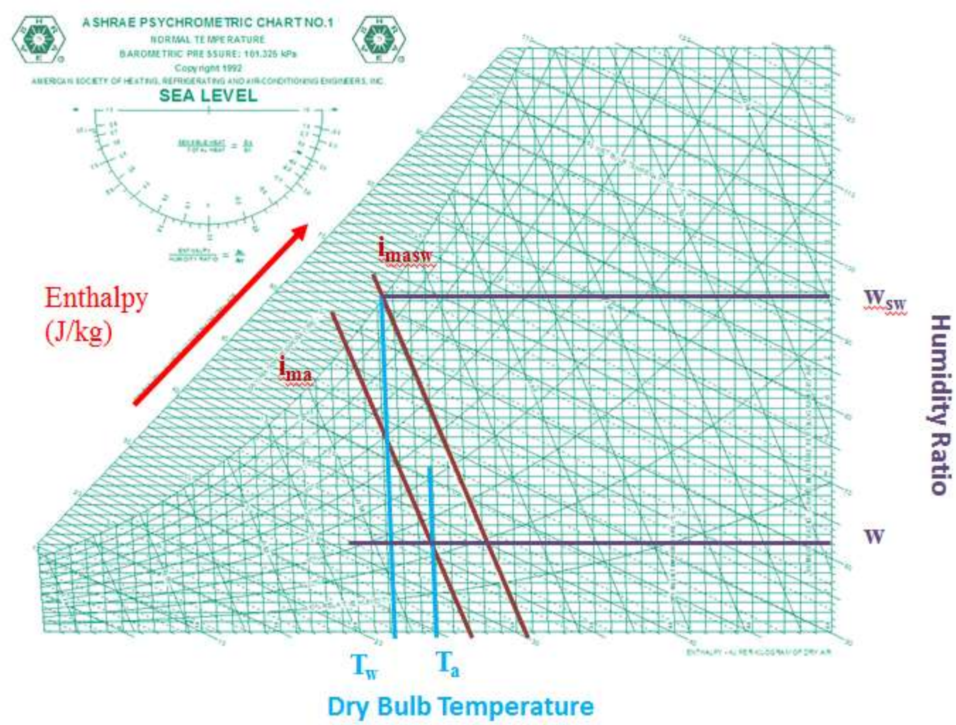


Figure 3 Enthalpy Transfer between water and air in a hot and dry condition (Kloppers, 2003)

The psychrometric chart was adopted in the industry, and various version of psychrometric charts were available where the general equations were of little differences (Dwyer, 2009, Gatley, 2008]. Shallcross (Shallcross, 1997), used physical properties to construct psychrometric charts suitable for various conditions, such as atmospheric pressure and at condition with different air compositions (79%N_2 and 90% N_2).

However, these psychrometric charts cannot allow the user to determine the situation when air condition exceeds the saturation point, where within the cooling tower, air beyond saturation still has the potential for latent and sensible heat transfer (Goyal, 2000, Droger, 1998). Kroger (Kroger, 1998) has included the super-saturation region in the psychrometric chart as shown in Figure 4.

The super-saturation region can help to determine a more reliable plume evaluation (Kloopers, 2003), thus able to organize the plume abatement program to be more effective.

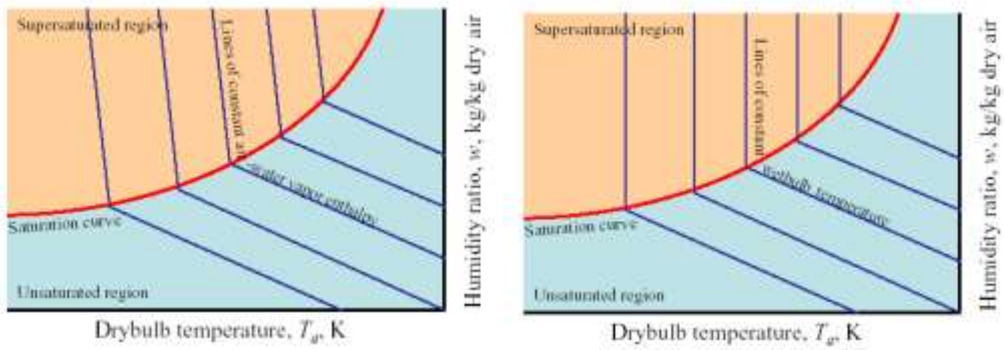


Figure 4 Enthalpy (left) and Wet bulb temperature (right) lines at supersaturation (Kloopers & Kroger, 2004)

2.2.2 Types of Cooling Tower

Cooling tower is developed based on the heat and mass transfer between air and water to achieve water cooling. Numerous publications have described the development, performance and selection of cooling tower (Kroger, 1998, Mohiuddin & Kant, 1995, Milosavlievic & Heikkila, 2001). For cooling tower, the most important factor is the Liquid to Water (L/G) ratio, as it correlates with the tower characteristic and performance. This ratio is determined by the shape of the cooling tower, height of the fill and the roughness of the fill (Thomas & Houston, 1959, Lowe & Christie, 1961, Goshayshi & Missender, 2000).

Cooling tower is generally considered as individual equipment from the main cooling system, and is usually ignored until any crisis occurs. At present, as the world is paying more attention in energy saving opportunity, more attention is focused in the design of cooling tower to allow for maximum performance.

Performance of cooling tower is usually determined by two terms; range temperature and approach temperature. The range temperature is the difference in temperature of water inlet and water outlet through the tower, while the approach temperature is the difference between the ambient wet bulb temperature (WBT) and the water outlet temperature. The heat transfer of cooling tower is between water and air. Sensible heat transfer is via heat absorption from water to air and latent heat transfer is via the release of heat of vaporization from water, which accounts for 25% and 75% of the total heat transfer respectively (Muangnoi et al, 2007).

The performance of cooling tower is not accounted by the amount of heat rejected, but rather on the level at which the heat is rejected. Therefore, the performance is determined by the relationship between cold water temperature and the atmospheric condition, which is either the wet bulb temperature (Coffey & Home, 1914) or the RH (Walker et al, 1937) of ambient air. London et al (London et al, 1940) suggests that the cooling tower process is driven by the enthalpy potential differences. Though different parties have different arguments, it is agreed amongst the different parties that water evaporation must be included to allow for realistic heat and mass transfer.

Cooling tower can be characterized into different categories, such as the air circulation pattern, the relative direction of air and water flow, the shape of cooling tower and the method of heat transfer (Mohiudden & Kant, 1995). In terms of air circulation, it is separated into natural and mechanical draft. Natural draft cooling tower is designed to allow air to flow through the tower by buoyancy.

The first natural draft cooling tower was constructed in 1916 in Netherland (Bowman & Benton, 1997), and the tallest cooling tower was constructed with 200m high at Niederaussem Power Station in Germany (Busch et al, 2002).

Figure 5 shows a structural layout diagram and an outlook of a natural draft cooling tower, which demonstrates the enormous structure and size of it in comparison to nearby buildings.

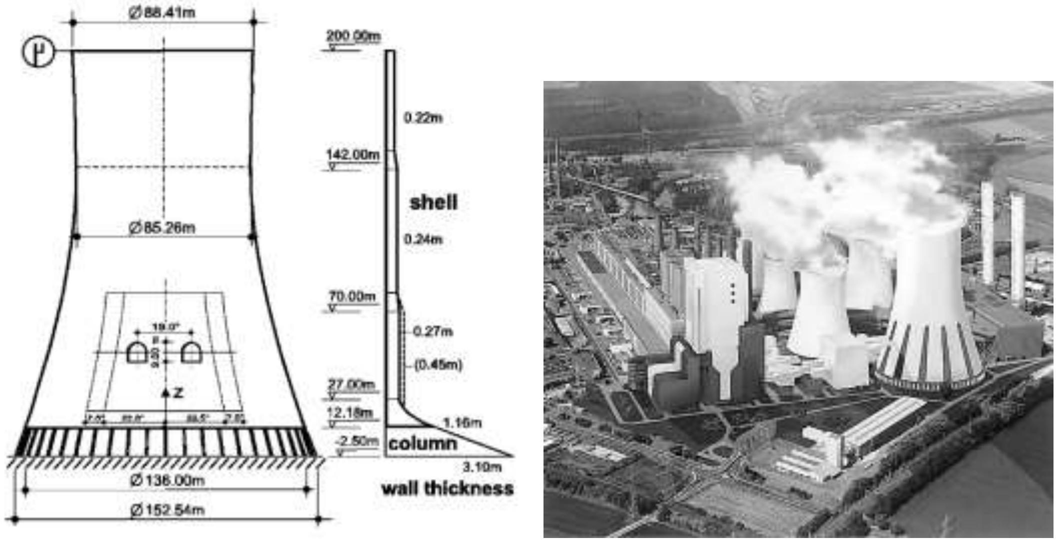


Figure 5 Natural Draft Cooling Tower (Busch et al, 2002)

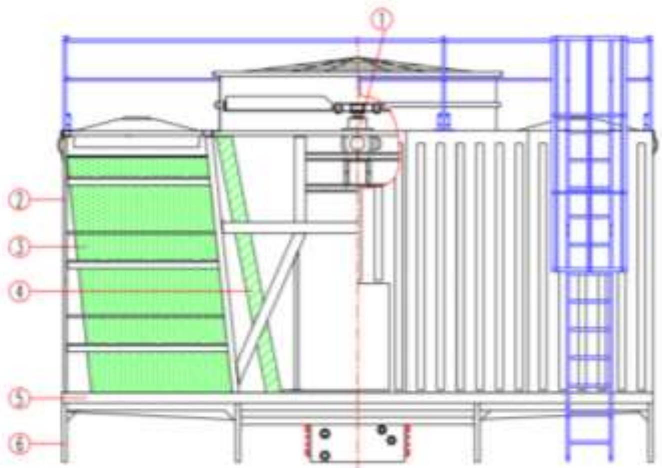
Mechanical draft cooling tower, on the other hand, is much smaller in size and less expensive to build comparatively. Although it is smaller in size compared to natural draft cooling tower, it requires mechanical transmissioning system, such as motor and fan, to operate. The cost of power for the fans and any associate equipment is still considerable large (Mohiudden & Kant, 1995).

If the fan is installed at the bottom of a cooling tower, it is commonly known as the force draft; whereas if the fan is installed at the top of a cooling tower, it is known as the induced draft. Mohiuddin and Kant have listed out the selection dependent factors between the two types of fan arrangements, which included the air recirculation, the power consumption, the approach temperature, the WBT, the noise intensity, the impact of vibration and the maintenance cost (Mohiudden & Kant, 1995).

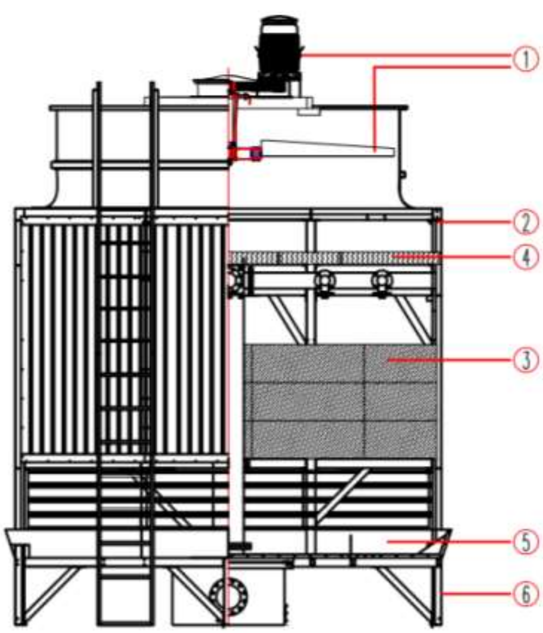
Any cooling towers can be further classified as either crossflow or counterflow. The difference between the two is the flow pattern within the cooling tower. Figure 6 shows a crossflow cooling tower (left) and a counterflow cooling tower (right). During the 1970s and 1980s, crossflow was used more often than counterflow in industry because of the utilization of traditional wood slat splash bar fill, which allowed crossflow to be more efficient in heat transfer and smaller in scale when dealing with the same heat load. However, as efficiency increases, densely packed materials are becoming available to manufacture fill, the counterflow cooling tower can be constructed with smaller size, lower pumping power and lower initial costs (Burger, 1994). Table 2 illustrates the comparison between the two types of counterflow and crossflow cooling tower

Table 2 Summary of Performance Comparison between crossflow and counterflow cooling tower (Burger, 1994)

	Counterflow	Crossflow
Water distribution	Lower HP pumping head	Up to 50% higher riser
Recirculation	No intendancy	Reduction in performance
Capacity	50% more with cellular fill	Too costly for film fill
Icing	Controllable with Aux piping Reverse fan more effective	Louver icing prevalent Too high a profile to be heated
Future Expansion	Fill depth easily increased	No inexpensive capability
Maintenance	Easier access to components Cold water basin open	Interior height dangerous Cannot clean the cold water basin
Fan Horse Power (HP)	Less usually required	More HP for same work
First Cost	Larger capacity towers, less	Costs more for same work



ITEM	PARTS
1	TRANSMIISSIONING SYSTEM
2	FRAME WORK
3	FILL
4	DRIFT ELIMINATOR
5	COLD WATER BASIN
6	TOWER SUPPORT STAND



ITEM	PARTS
1	TRANSMIISSIONING SYSTEM
2	FRAME WORK
3	FILL
4	DRIFT ELIMINATOR
5	COLD WATER BASIN
6	TOWER SUPPORT STAND

Figure 6 Layout of crossflow (left) and counterflow (right) cooling tower

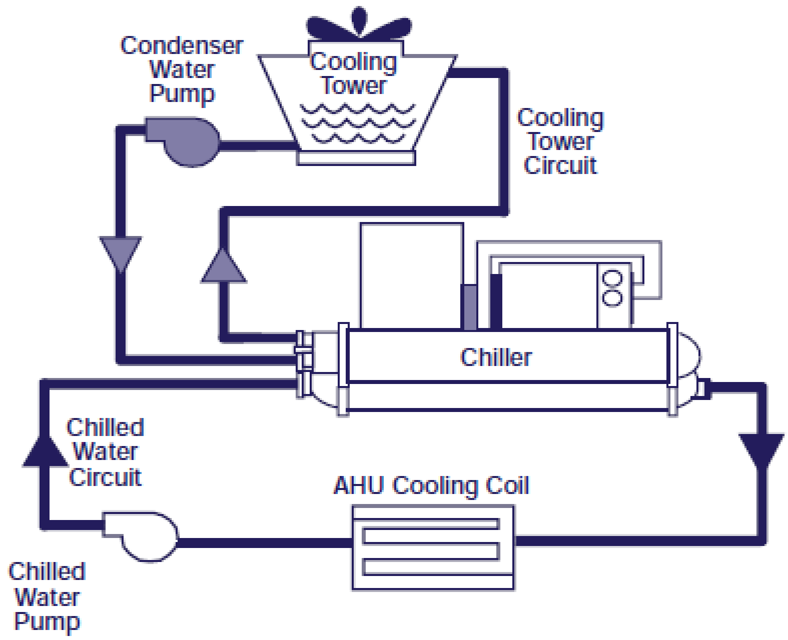


Figure 7 Schematic Drawing of any types of mechanical draft cooling tower system in building (Thomas, 2000)

As tower is drawing air into the tower, it is possible that a portion of the discharged air is drawn back into the tower as shown in Figure 8, which is known as the re-circulation. This issue occurs to both crossflow and counterflow cooling tower. The re-recirculation effect is more severe for counterflow cooling tower as the fan is located at the intake side and much easier to draw discharge air back to the intake point.

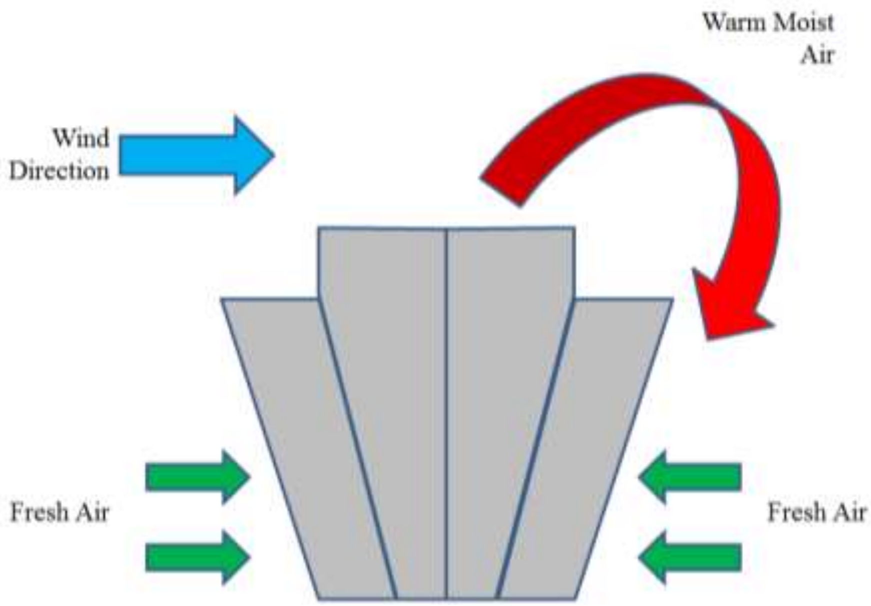


Figure 8 Recirculation of cooling tower (Burger, 1994)

During the heat transfer process, much water in small droplets size would flow along the air passing through the tower. These droplets are known as drifts, and are a serious concern for cooling tower with respect to health issue.

2.2.3 Cooling Tower, Legionella Growth and Droplet Dispersion

Drift of small water droplets in cooling tower may contain water treatment chemicals or bio-organisms, such as Legionella (Meroney, 2008), which is harmful to human health. Cooling tower is also a perfect environment for Legionella to grow as shown in Figure 9 (Legg, 1991).

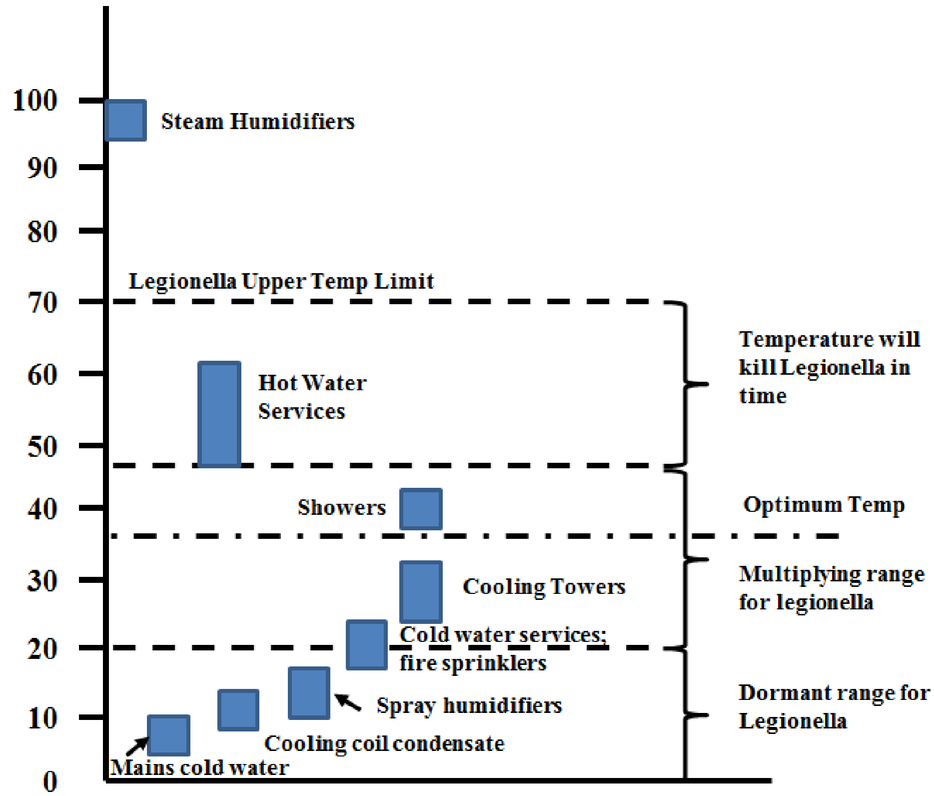


Figure 9 Temperature range in water for building services equipment and suitable environment for growth of Legionella (Legg, 1991)

Figure 10 (DoH, 2010) shows the statistics of the occurrence of Legionnaire's Disease. The peak is at 2009 with 37 cases. Incidentally, up to April 2009, 162 Water-cooled Air Conditioning System (WACS) had been installed. Whether any correlation existing is not clear, but the decrease in number of cases could be due to more stringent regulation on the water treatment of cooling towers.

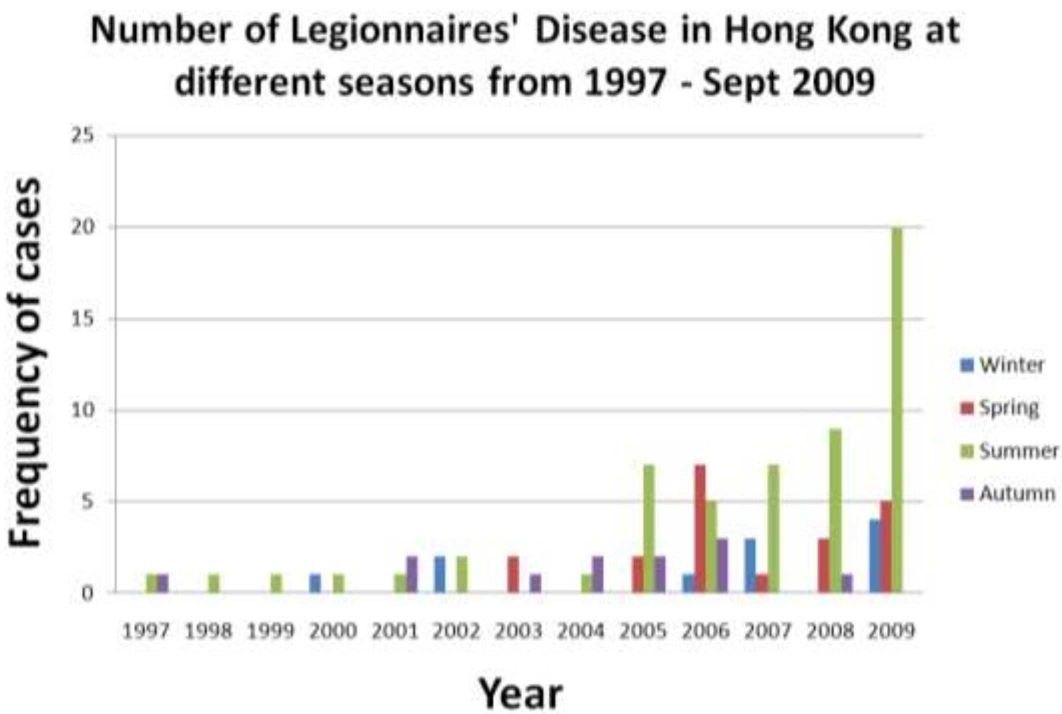


Figure 10 Statistics of detected cases for Legionnaire's disease in Hong Kong under different seasons (DoH, 2010)

The dispersion of contaminated droplets is determined by the size of the droplet, as well as the wind direction and wind velocity. As a free-living legionella is 1- 3μm long and 0.30.9μm wide (Rodgers, 1978), it can survive in aerosolized water droplets with diameter range from 1-15μm (Percival et al, 2004, Hart & Makin, 1991). The size of drift droplets is determined by the discharge air velocity; the higher the velocity, the bigger the size of drifts droplets as shown in Table 3 (Brin, 2002). Meroney suggests that the mean diameter of drift droplets, which has low effect from gravitational force can range from 0.1mm to 1mm (Meroney, 2008, Valley, 2009).

Table 3 Minimum radius of droplet at a specific velocity (Brin et al, 2002)

Air Speed (m/s)	Min Droplet Radius that would flow along air flow at specific speed (mm)
0.5	0.5
1.0	1.0
1.5	1.5
2.0	2.0
2.5	2.5

As countless of small droplets are flowing along with the air, these droplets may experience re-condensation when mixed with the ambient air condition, creating a severe visible plume. Although modern high-rise buildings conceal itself from outdoor environment to maintain a controlled indoor environment, evidence has shown that outbreak of Legionnaires' Disease is linked with the contamination of air conditioning and ventilation system (Johnson et al, 1985).

2.3 Basics of Visible Plume of Cooling Tower

Many studies have been carried out on visible plume. Visible plume may appear when there is a sudden drop of air temperature that reduces the moisture holding capacity of a unit volume of air. As a result, the moisture will then be "rejected" from the air particles, and condenses to form visible plume.

Several models have been carried out to identify the impact of visible plume by using numerical models to predict visible plume region of cooling towers. One of which is a simple algebraic model developed by Hanna (Hanna et al, 1976), yet the disadvantage of this model is that it cannot accurately "predict the visible plume region under high RH" (Michioka et al, 2007). Another model for visible plume impact is developed by Policastro (Policastro et al, 1994) to predict the Seasonal/Annual Cooling Tower impact (SACTI) and to predict the impact of visible plume from any number of mechanical cooling towers. These two models are acceptable to identifying the normal behavior of the visible plume.

However, as the atmospheric condition continues to change, and the real plume behavior is difficult to predict, the use of numerical models alone is insufficient to identify the impact of visible plume under different climatic conditions (e.g. change in temperature, RH, wind speed and wind direction). With this in mind, Computational Fluid Dynamics (CFD) is adopted on several cases to study the pattern of visible plume (England et al, 1973 & Takata et al, 1996).

Although CFD simulations are very useful to carry out in-depth analysis on the impact of visible plume pattern, several researches carried out wind tunnel testing in order to prove the physical relationship between plume and the outdoor climatic environment.

Kennedy and Fordyce (Kennedy & Fordyce, 1974) carried out wind tunnel experiments and identified the interaction between plume and different wind conditions. Michioka (Michioka et al, 2007) also carried out wind tunnel testing, which the experiment used tracer gas and high-response flame ionization detectors to identify the plume formation under cross-wind condition to predict visible plume region. The results were compared with observation obtained from a mechanical-draft cooling tower of the Benning Road plant, and validation results showed that the tracer gas plume is almost in agreement with the observations and concluded that the methodology is sufficient to predict the visible plume region of a cooling tower.

2.4 Visible Plume Abatement

In the earlier industrial period, visible plume had always been accepted by general public as it was a sign of thriving manufacturing industry. However, as more concerns were raised to the visibility of cooling tower plume and study cases were carried out. One of the cases was the Chicago's O'Hare Airport, where cooling towers were placed between the FAA control tower and the airport runways (Randall et al, 1998). Due to the nature of the construction, visible plume should not occur in the environment where there could be disturbance by obstructing the visibility between the control tower and the runways.

Figure 11 shows the site layout plan of the airport and the location of the towers within in the airport site boundary.

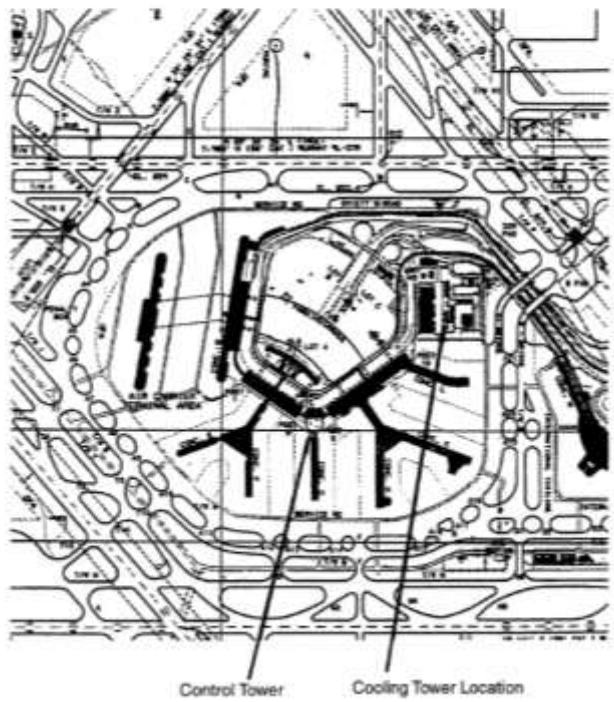


Figure 11 Site plan of the Chicago's O'Hare Airport and the specific cooling tower locations (Randall et al, 1998)

In order to understand how plume would occur, psychrometric chart is one of the best tools to use to explain the phenomena. Figure 12 shows a psychrometric chart with the yellow color high-lighted area is where potential of plume would occur when discharge air will drops in temperature significantly and causes the air to have a lower capacity to hold moisture, and thus leading to condensation. Severity of the visible plume is also illustrated on the very same diagram; where the larger the high-lighted area is when severity of plume worsens.

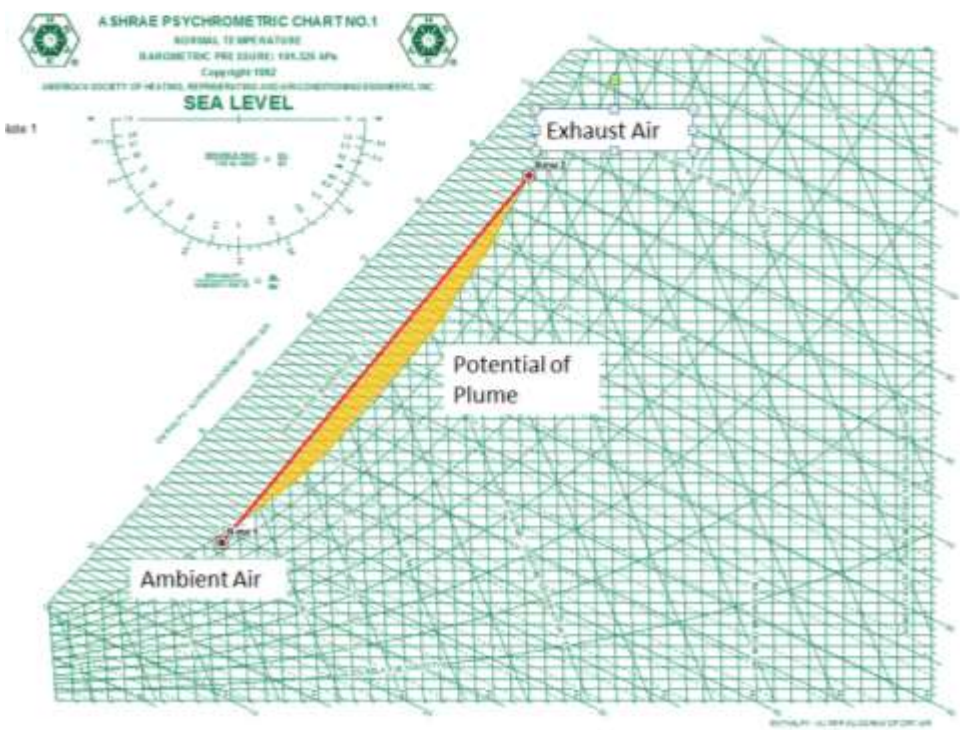


Figure 12 Psychrometric chart showing that exhaust air with high humidity ratio (Cooling Tower Moist Air Discharge) would lead to high potential of visible plume under the specific discharge and ambient air condition (Tyagi et al, 2012)

Visible plume occurrence is not limited in Hong Kong and can occur at any sub-tropical regions where serious visible plume formation can be identified during winter and spring seasons (Wang et al, 2009). In order to reduce visible plume in the environment, several approaches were developed. The most common one was the adoption of heater for plume abatement cooling tower as shown in Figure 13.

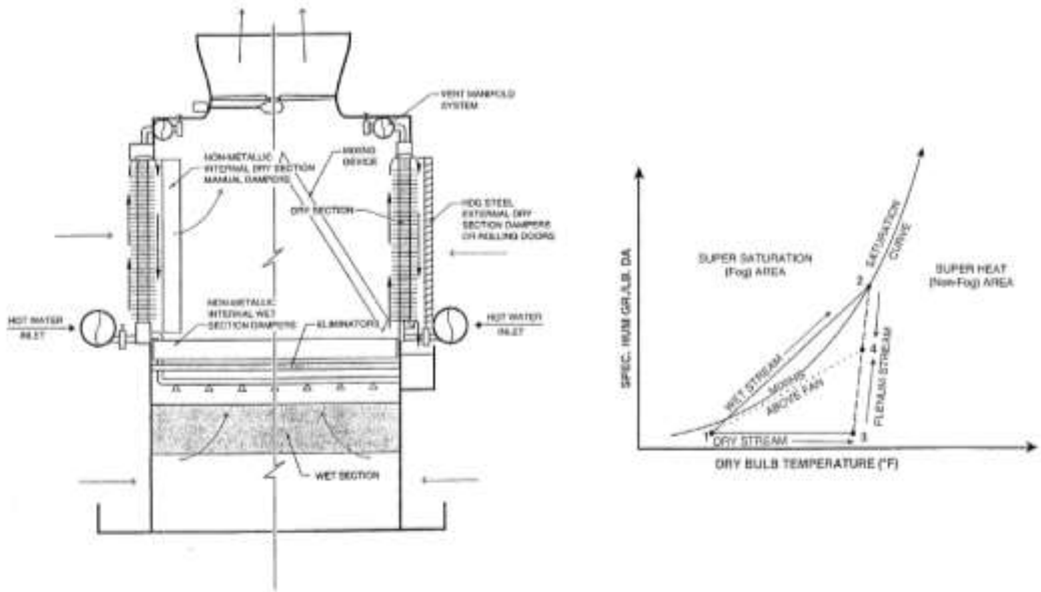


Figure 13 Configuration of a cooling tower with heater for visible plume abatement purpose (Randall et al, 1998)

This configuration of cooling tower is to simply place heating coils above the fill as shown in Figure 13 and the water sprinkler section (reduce contact potential with moisture), and draws air into the tower when visible plume abatement is required. The heating coils (either hot water coil or electrical heating coil) can effectively heat up the air that passes through the tubes. Heated air will then mix with the moist air passing through the fill at the lower section of the tower, and inevitably reduces the RH before leaving the tower. This approach effectively reduces the chance of visible plume. In theory, it is possible to eliminate visible plume completely depending on how much heat source can be provided on site.

Fishers (Fisher, 1994) and ASHRAE (ASHRAE, 1996) suggested alternative approaches for visible plume abatement, such a natural gas burner, steam coils, precipitators installation and chemicals spraying at the exhaust point. However, it was also concluded by the authors that these approaches were quite expensive and were not always effective in reducing visible plume.

With respect to this, Wang and Tyagi (Wang & Tyagi, 2006 and Tyagi et al, 2007) proposed to use heat pump instead of hot water / electric heater to provide the heating required for visible plume abatement as heat pump was higher in COP comparatively.

However, heat pump is not very common in a city with sub-tropical climatic condition. Wang (Wang et al, 2007) proposed an alternative to use solar energy to control visible plume with solar collector based on the Singhal's theory (Singhal, 2003).

Solar collector is used to heat up the circulating fluid and transfer the stored heat to a heat exchanger in order to heat up the cooling tower exhaust before it leaves the tower. The arrangement of this system is as shown in Figure 14.

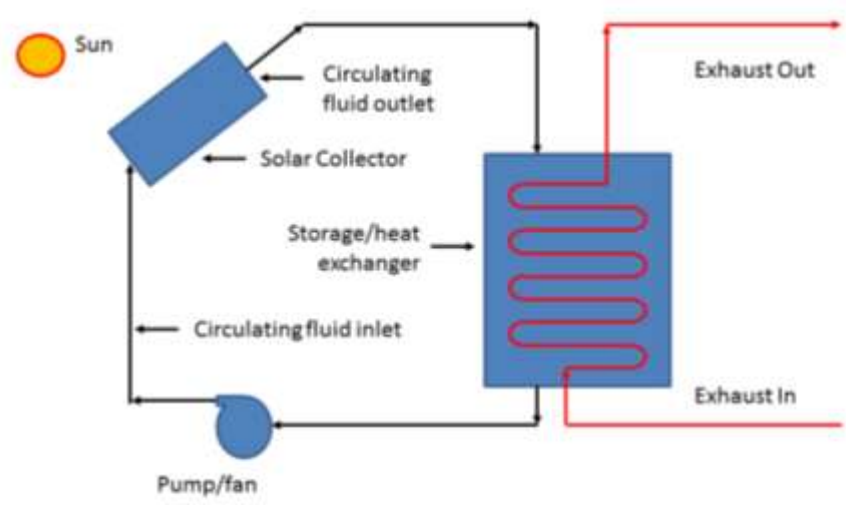


Figure 14 Configuration of the use solar collector to heat the cooling tower exhaust (Wang et al, 2006)

In the industry, another visible plume abatement approaches is to increase the air flow rate of cooling tower as it can reduce slightly the temperature and humidity level of discharge air while meeting the heat rejection rate. Researches have carried out to identify the effect of visible plume abatement by altering the air flow rate across the tower [Shelton & Weber, 1997]. As the cooler air has a lower dry bulb temperature, the amount of moisture that air can absorb will be much less than the hotter air during typical operating condition. By increasing airflow rate to discharged air at a lower temperature compared to a higher temperature, condensation will be reduced as shown in Figure 15.

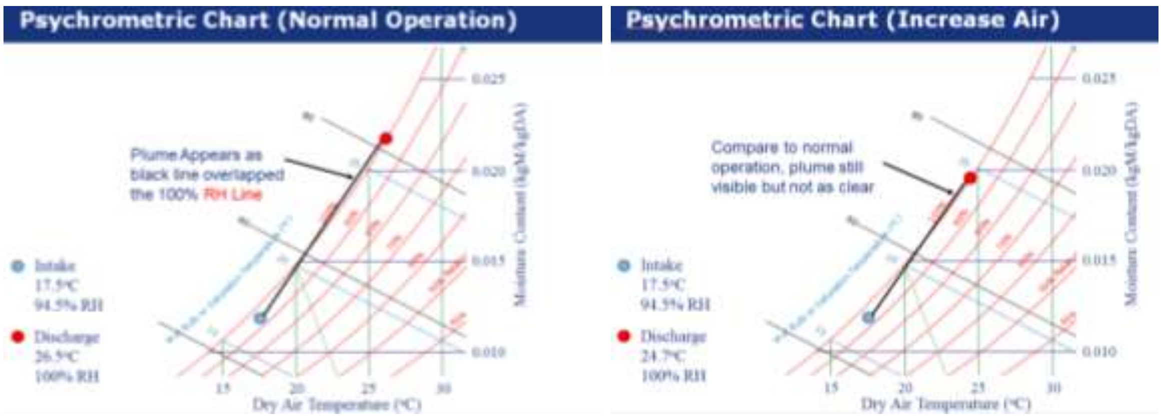


Figure 15 Visible plume severity comparisons on psychrometric chart with increase airflow rate approach

Alternatively, visible plume abatement can be carried out by wet-dry fill approach by introducing an air-stream through fill area where there is no water flowing downwards as shown in Figure 16. This allows a portion of unheated and un-humidified ambient air to mix with the hotter and more humid air within the tower before discharged into the outdoor environment.

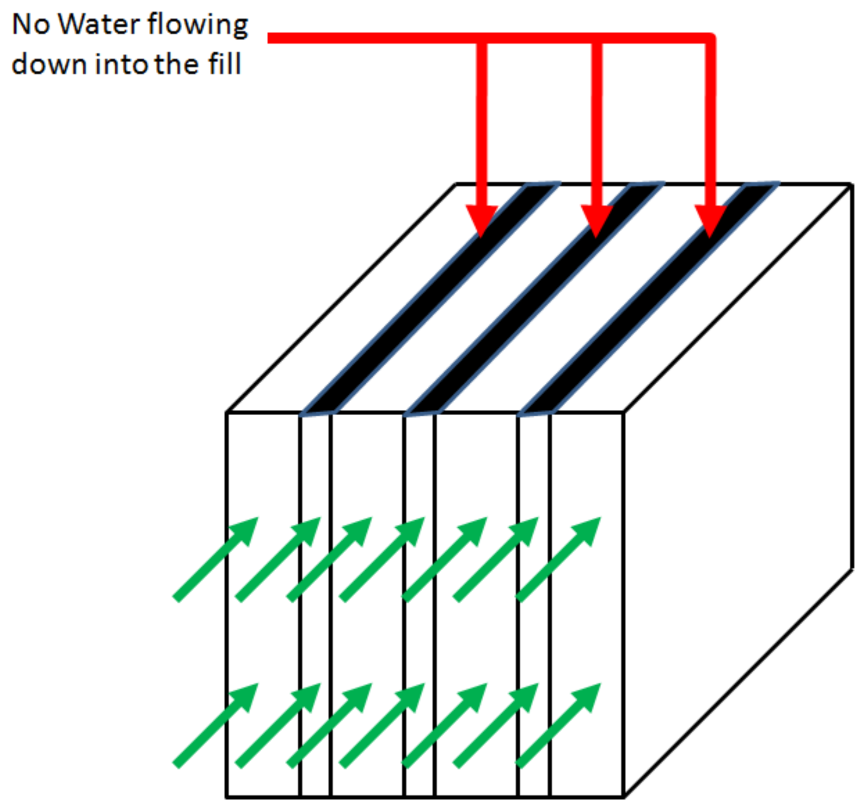


Figure 16 Configuration of an over-sized cooling tower to reduce chance of visible plume

Although visible plume abatement could be carried out solely by implementing a heating component in a cooling tower, Xu (Xu et al, 2007) carried out visible plume elimination by studying the control logic of the entire cooling plant and developed a control strategy that would reduce the potential of visible plume. A large commercial building in Hong Kong was used to carry out his analysis, and it was concluded that visible plume abatement could not be predicted in advance as variables such as outdoor air condition, arrangement of cooling towers, and the required heat rejection change continuously throughout the year. Xu concluded that the strategies for cooling tower to reduce visible plume occurrence would be to use a constant set-point supply cooling water temperature control logic and fan modulation methods in commercial building

2.5 Summary

The basic function of a building is to provide occupants with a comfortable environment, which requires HVAC System to achieve the objective. As WCC is more effective in heat rejection compared to ACC, it is practical to use cooling tower often in Hong Kong with abundant of purchased water supply. However, visible plume is a problem when using cooling tower, which visible plume creates a nuisance to human comfort and health risks. In this respect, visible plume abatement is carried out. There are several plume abatement approaches available in the industry, such as adopting heating coil, wet-dry fill approach and HVAC plant system control.

Chapter 3 – Heat Transfer Mechanism of the Cooling Tower

3.1 Mathematical Model of Cooling Tower

Cooling towers can be separated into two major types, natural draft and mechanical draft. Mechanical draft cooling towers are widely used for high-rise buildings, as it is more compact in size and flexible in allocation arrangement. Ambient air is forced into the tower with the utilization of fan to cool down the circulating water.

The fundamental heat and mass transfer theory of cooling tower operation was proposed by Walker with a series of basic equations and separated the whole process into different parts for calculation since many coefficients of sensible heat and mass transfer were involved (Mendes et al, 2008, Walker, 1923). Merkel published the numerical model in 1925 by compiling all the coefficients into an overall coefficient that corresponding with the enthalpy difference between saturated air and the air at the point of contact with water (Merkel, 1925). However, it was overlooked until 1941 when the published paper was translated into English (Osterle, 1991).

The benefit of the Merkel Approach is to allow for quick and easy approximation of the tower thermal performance at various experimenting operating condition, as well as the discharge air condition. The Merkel Approach is developed with three critical assumptions;

- The Lewis factor (Le_f) is maintained at a fixed value of 1
- Assuming no water is lost through evaporation
- The discharged air is assumed to be at saturation with water vapor

3.1.1 Lewis Factor

In order to understand what Le_f is, the Lewis number (Le) must first be understood. The Le_f is derived from Le, which is the ratio between Prandtl number (Pr) and Schmidt number (Sc). Pr is a dimensionless factor that describes the ratio of kinematic viscosity to thermal diffusivity and Sc is a dimensionless factor that describes the ratio between momentum diffusivity and mass diffusivity.

In the derivation of these two numbers, three fundament factors must be identified. They are the rate of change of momentum, the rate of change of heat and the rate of change of mass; in which equations are derived from the theory of Newton's law of viscosity, Fourier's law of heat transfer and Fick's law of diffusion respectively with the representative equations as shown below.

Newton's law of viscosity $$\frac{F}{A} = \mu cell = v\frac{\partial(\rho u)}{\partial y} \quad (1)$$

Fourier's law of heat transfer $$\frac{Q}{A} = k\frac{\partial T}{\partial y} = \alpha\frac{\partial(\rho c_p T)}{\partial y} \quad (2)$$

Fick's law of diffusion $$\frac{\dot{M}}{A} = D\frac{\partial c_i}{\partial y} \quad (3)$$

There are one diffusivity in each equation, which are ν, α and D. As each of these diffusivity contains the ratio of L/T, which represents length and time scale respectively, thus the ratio of the two coefficients resulting with a dimensionless number. In a heat transfer that involves instantaneous momentum and mass transfer, the ratio of ν to D is extremely important and is termed as a Schmidt number. Equation (4) shows the equation for Schmidt number.

$$Sc = \frac{v}{D} \quad (4)$$

Whereas, with a system that has an instantaneous convective momentum and heat transfer, the ratio of ν to α are important and is termed as Prandtl number. Equation (5) shows the equation for Prandtl number.

$$Pr = \frac{v}{\alpha} \quad (5)$$

In an evaporation process, there is always an involvement between convective heat and mass transfer, which can be expressed in the ratio between the Schmidt number and the Prandtl number as shown in Equation (6).

$$Le = \frac{Sc}{Pr} = \frac{k}{\rho c_p D} \quad (6)$$

This equation allows for calculation of the Lewis number (Le), which determines the heat and mass transfer rate in an evaporative process. If Le equals to 1, the temperature and concentration profile will have a linear relationship.

Lewis, the person who developed the Lewis number, tried to demonstrate that Lewis number was unity for gas/liquid system through numerical approaches (Lewis 1922). In a following publication, Lewis claimed that the theory of Lewis number was almost always at unity (Lewis, 1933). This theory remained valid for a long period of time, and resulting with Merkel in believing that "Lewis number (Le) should equal unity for moist air at a normal condition of temperature and pressure" (Jones, 2001).

However, Dreyer (Dreyer, 1988) studied the Lewis number, and claimed that the statement Lewis made was incorrect. In additional, Sutherland suggested that the Merkel approach undersized the actual cooling tower performance by 5% ~ 15% when a "true" mass transfer coefficient was considered.

With this in mind, the Lewis factor (Le_f) is introduced to describe the heat and mass transfer process in an evaporative process, and this new term is used in cooling tower very often and is described by the heat transfer Stanton number, St, as shown in Equation (7), and the mass transfer Stanton number, St_m, as shown in Equation (8).

$$St = \frac{Nu}{RePr} \tag{7}$$

$$St_m = \frac{S}{ReSc} \tag{8}$$

The relationship between these two numbers for Lewis factor is as described below in Equation (9):

$$Le_f = \frac{St}{St_m} \tag{9}$$

Given that Lewis's theory was inaccurate, researches were carried out to discover the relationship between Le and Le_f. It was found that the relationship could be explained when the Chilton-Colburn analogy power law relations was adopted (Mills, 1995), then the relationship between Le and Le_f would be expressed as shown in Equation (10).

$$Le_f = \left(\frac{Pr}{Sc}\right)^{-\frac{2}{3}} = Le^{\frac{2}{3}} \qquad (10)$$

In the calculation for evaporative cooling approach in cooling tower, Le_f is approximately 0.92 (Sutherland, 1983).

3.1.2 Evaporation

If a true evaporating cooling process must be taken into account of in the model, then evaporation cannot be neglected. The amount of evaporation is controlled by the Liquid to Gas (L/G) ratio, which in this case represents water flow rate for the former and airflow rate for the latter respectively.

3.1.3 Sophisticated Mathematical Modeling

Physically, it is unreasonable to assume that air at discharge of any cooling tower is at saturation condition. As computational power increases significantly, a more sophisticated model is inevitably required in order to develop a more accurate control strategy. Another approach to calculate cooling tower performance is the e-NTU approach; however, this approach makes similar assumptions as the Merkel approach, and thus the calculated results from both approaches are very similar (Poppe & Rőgener, 1991). Bourillot suggests that the Merkel approach is capable in estimating the water temperature, but unable to account for the evaporative effect and the moisture content of discharge air (Bourillot, 1983).

It is generally accepted that as air saturates while travelling through the fill and loses the ability to absorb heat from water. However, Goyal states that such theory is a misconception (Goyal, 2000). Saturated air within a confined space still has the potential in absorbing additional heat and moisture from water and becomes a state of super-saturation, which will turn into mist immediately when comes into contact with ambient air. Since Merkel approach cannot accounts for the gain in moisture of cooling tower, it is essential to use a more accurate approach instead of the Merkel approach to enhance control strategy.

Poppe approach, developed in the 1970s by Poppe and Rőgener (Poppe & Rőgener, 1991), did not make simplified assumptions as the Merkel approach. The Poppe Approach provided a more appropriate discharge condition as it the calculation takes into consideration of water temperature, water mass flow rate, air humidity and air temperature. The advantage of Poppe approach is that it can calculate the moisture content of air at discharge which Merkel approach cannot, regardless of whether it is at unsaturated condition or supersaturated condition. Evaporation of water is also taken into consideration in the Poppe approach, which allowed for more accurate heat rejection rate calculation (Kloppers & Krőger, 2005). Moreover, as water evaporation is calculated, calculation makeup water will become more reliable.

Figure 17 illustrates the heat and mass balance in a crossflow cooling tower, where air flows horizontally across the fill and water flows downward vertically. i_{ma} and w represents enthalpy and moisture content for air side respectively, and G_w and T_w represents flow rate and temperature for water side respectively.

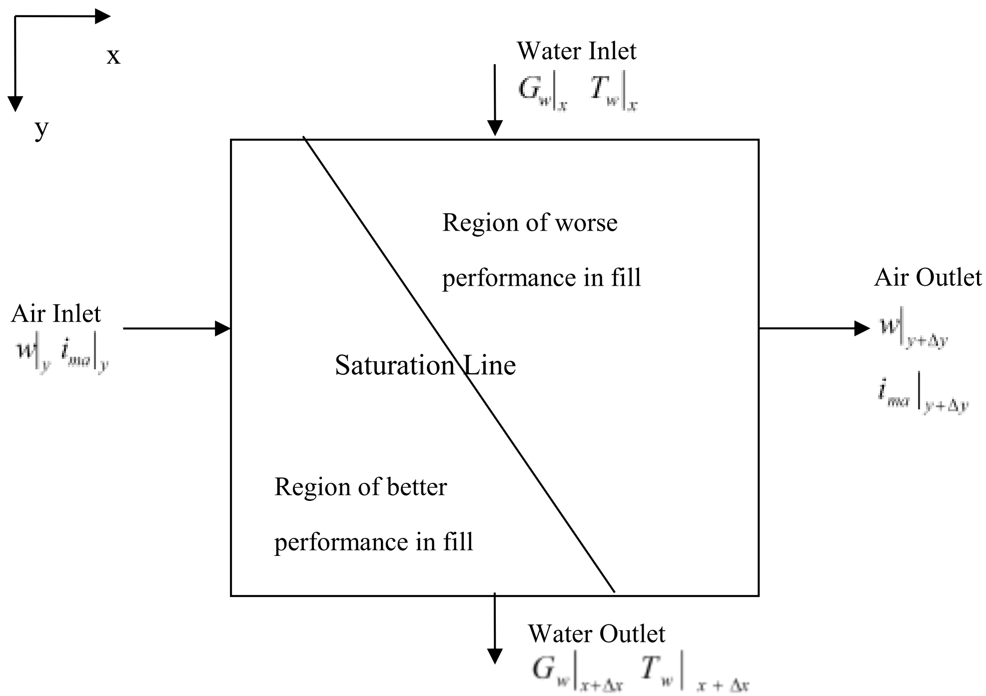


Figure 17 interior operation of a crossflow cooling tower

Where

x	Distance air travelled in x-direction
y	Distance water travelled in y-direction
G_w	Mass flow rate of water
T_w	Temperature of water
w	Moisture content of air
i_{ma}	Enthalpy of air

Equations (11) – (14) are the differential heat and mass transfer equations adopted in a cross-flow cooling tower for un-saturated conditions.

$$\frac{\partial G_w}{\partial y} = -G_a \frac{h_d a_{fi}}{G_a}\left(w_{sw} - w\right) \tag{11}$$

$$\frac{\partial T_w}{\partial y} = \frac{G_a}{c_{pw} G_w} \frac{h_d a_{fi}}{G_a}\left[\begin{array}{l}(w_{sw} - w)c_{pw} T_w - (i_{masw} - i_{ma}) - \\ (Le_f - 1)[i_{masw} - i_{ma} - i_v(w_{sw} - w)]\end{array}\right] \tag{12}$$

$$\frac{\partial w}{\partial x} = \frac{h_d a_{fi}}{G_a}\left(w_{sw} - w\right) \tag{13}$$

$$\frac{\partial i_{ma}}{\partial x} = \frac{h_d a_{fi}}{G_a}\left[i_{masw} - i_{ma} + \left(Le_f - 1\right)\left[i_{masw} - i_{ma} - i_v\left(w_{sw} - w\right)\right]\right] \tag{14}$$

The Lewis factor (Le_f) in the Poppe approach is calculated from the equation proposed by Bosnjakovic (Goyal, 2000), which at points when air is unsaturated is as follows:

$$Le_f = 0.865^{0.667}\left(\frac{w_{sw} + 0.662}{w + 0.622} - 1\right) \Bigg/ \left[\ln\left(\frac{w_{sw} + 0.622}{w + 0.622}\right)\right] \tag{15}$$

When air becomes supersaturated, the equation to calculate Lewis factor at supersaturation condition (Le_{fss}) is shown as follows:

$$Le_{fss} = 0.865^{0.667}\left(\frac{w_{sw} + 0.662}{w_{sa} + 0.622} - 1\right) \Bigg/ \left[\ln\left(\frac{w_{sw} + 0.622}{w_{sa} + 0.622}\right)\right] \tag{16}$$

Equations (17) – (20) are the differential heat and mass transfer equations adopted in a cross-flow cooling tower for supersaturated conditions, which are as follow:

$$\frac{\partial G_w}{\partial y} = h_d a_{fi}\left(w_{sw} - w_{sa}\right) \tag{17}$$

$$\frac{\partial T_w}{\partial y} = \frac{G_a}{c_{pw} G_w}\frac{h_d a_{fi}}{G_a}\begin{bmatrix}\left(w_{sw} - w_{sa}\right)c_{pw}T_w - \left(i_{masw} - i_{ma}\right) - Le_f c_{pw} T_w\left(w - w_{sa}\right) - \\ \left(Le_f - 1\right)\left[i_{masw} - i_{ma} - i_v\left(w_{sw} - w\right)\right]\end{bmatrix} \tag{18}$$

$$\frac{\partial w}{\partial x} = \frac{h_d a_{fi}}{G_a}\left(w_{sw} - w_{sa}\right) \tag{19}$$

$$\frac{\partial i_{ss}}{\partial x} = \frac{h_d a_{fi}}{G_a}\left[i_{masw} - i_{ss} + Le_f c_{pw} T_w\left(w - w_{sa}\right) + \left(Le_f - 1\right)\left[i_{masw} - i_{ma} - i_v\left(w_{sw} - w\right)\right]\right] \tag{20}$$

Poppe and Rőgener, in order to simplify the calculation process, neglected the fill dimension in the calculation (Poppe & Rőgener, 1991). The Merkel number in the Poppe approach applied the first-order backward difference and incorporated into the Merkel equation and formed Equation (21), where ξ = x/L_x and η = y/L_y. L_x and L_y represents the fill in x and y direction respectively.

$$Me_{\xi} = h_d a_{fi} \Delta\xi / G_a = h_d a_{fi} \Delta\eta / G_a \tag{21}$$

H_d and a_{fi} are the mass transfer coefficient and surface area per unit volume of any particular fill respectively, which the latter is impossible to determine (Roth, 2001). By combining Equation (21) with Equations (11) – (14), the equations for sub-saturation will yield the following:

$$G_{w(i,j)} = G_{w(i,j-1)} - G_a Me_{\xi}(w_{sw} - w) \tag{22}$$

$$T_{w(i,j)} = T_{w(i,j-1)} + \frac{G_a}{c_{pw} G_w} Me_{\xi} \begin{bmatrix} (w_{sw} - w) c_{pw} T_w - (i_{masw} - i_{ma}) - \\ (Le_f - 1)[i_{masw} - i_{ma} - i_v (w_{sw} - w)] \end{bmatrix} \tag{23}$$

$$w_{(i,j)} = w_{(i,j-1)} - Me_{\xi}(w_{sw} - w) \tag{24}$$

$$i_{ma(i,j)} = i_{ma(i,j-1)} + Me_{\xi}\left[i_{masw} - i_{ma} + (Le_f - 1)[i_{masw} - i_{ma} - i_v (w_{sw} - w)]\right] \tag{25}$$

In order to solve for cooling tower performance, the Me_{ξ} will remain constant during the calculation until the calculated and experimented water outlet temperature are identical. The discharge conditions are determined also in the calculation. Poppe and Krőger have performed validation for cooling tower fill test (Kloppers, 2003).

However, in order to show that the Poppe Approach is an accurate approach to calculate the discharge air condition of any mechanical draft cooling tower, these sets of equation must be validated. Validation for a mechanical cross-flow cooling tower is presented in this thesis in respect to enthalpy which has taken into account of both temperature and RH. The validation process will be taken with a real size mechanical draft cooling tower as discussed in the following chapter.

The inputs require for discharge air calculation are inlet water temperature, outlet water temperature, water flow rate, inlet air dry bulb and wet bulb temperatures, and air flow rate. In order to validate the Poppe Approach, the discharge air condition (discharge air temperature and relative humidity) are measured to compare with the calculated discharge air condition.

3.2 Summary

The approach that has been used commonly in the cooling tower industry is known as the Merkel Approach. However, this approach is a simple calculation with many assumptions to accelerate the iteration, such as:

- The Lewis factor (Le_f) is maintained at a fixed value of 1
- Assuming no water is lost through evaporation
- The discharged air is assumed to be at saturation with water vapor

With these assumptions, the heat rejection condition calculated by the Merkel Approach is not very accurate. In order to calculate an accurate heat rejection rate condition, the more sophisticated Poppe Approach is used. This approach does not make the assumptions made in the Merkel Approach, thus is more accurate in predicting the heat rejection condition and the discharge air condition.

Chapter 4 - Full Scale Tests

With increasing computational power, it is essential to upgrade the calculation approach of cooling tower design as the outdated cooling tower models are partly responsible for the performance not achieving design condition (Burger, 1994). However, though the Poppe Approach has been validated with a natural draft cooling tower, there is no validation of the Poppe Approach for mechanical cooling towers that are smaller in size and more often used in buildings. Therefore, full scale tests have been carried out to validate the accuracy of this mathematical model.

4.1 Experiment Setup

The full scale test will required a full size mechanical tower, and this full size tower is constructed at a factory in Dongguan. In order to conduct the test, a heat source is required. Therefore, a heat source system is designed and constructed as shown in Figure 18, which consists of a real size cooling tower (see Figure 19), two sets of plate heat exchangers and a boiler.

The boiler operates with burning diesel to simulate the heat source of a building. The exit water temperature of the boiler is high with temperature that can reach up to 65^{o}C, which is too high for cooling tower (fill in cooling tower will melt when water temperature reaches above 50^{o}C per manufacturer design) and not a realistic temperature in building when operating cooling tower temperature in industry is usually between 20 – 40^{o}C, depending on the seasonal effect.

The test was conducted in 2009, and in order to achieve steady state, the ambient WBT must remain steady for a minimum of one hour. During the test, multiple tests are conducted and only one set of data meet the stability requirement. As the test is very costly due to high consumption of diesel, the manufacturer ceased further experiment after one successful experiment.

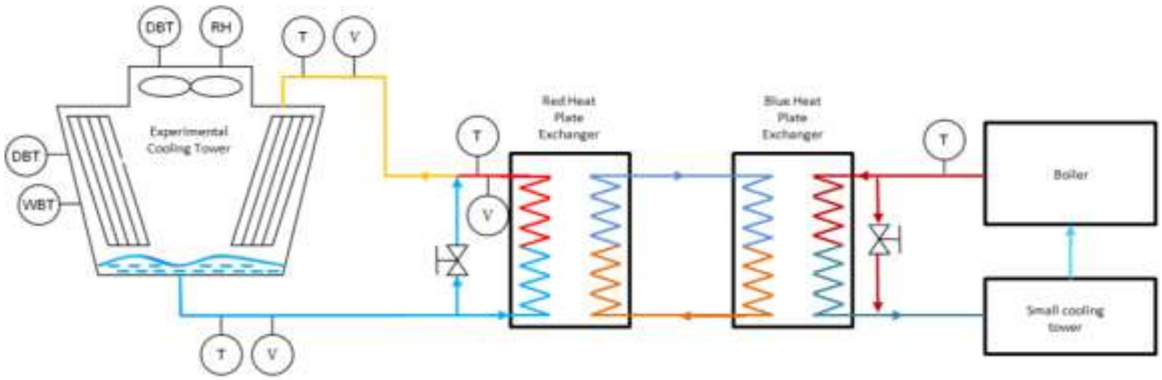


Figure 18 Schematic diagrams of the experimental setup for mechanical crossflow cooling tower (Give sensor abbreviation a key, e.g. T = temperature)

Figure 19 Cooling tower used for the experiment for Poppe Approach Validation

The cooling process in a cooling tower is through evaporative cooling, which is highly dependent on the ambient air condition, especially the WBT. In a typical design of a water cooling system, it is preferred to have the range temperature to remain at 5.0°C in order for the water cooled chillers to operate efficiently. Since ambient temperature cannot be controlled, the only variable that could be changed is the water mass flow rate. Therefore, ambient air condition is the most crucial parameter during the experiment and with close monitoring of the WBT in order to maintain a steady testing condition (1 hour) to reduce any unnecessary fluctuations in the data.

The experiment was conducted with WBT of 28.0°C with water flow rate flowing across the tower was approximately 350 m^3/hr. In order to cool the large amount of water to the desirable design water temperatures, an air flow rate of 313,000 m^3/hr was required and the tower was equipped with a 15 kW motor to draw that amount of air into the tower. The motor installed to drive the fan are shown in the left figure of Figure 20.

With this design configuration and a steady ambient condition, the water temperature at inlet and outlet during the experiment were maintained at 35.5°C and 30.5°C respectively.

Water was delivered to the cooling tower through an inlet pipe as shown in right figure of Figure 20 and was evenly distributed into the cooling towers

Figure 20 Cooling tower fan and the fan motor at the top of the cooling tower (Left) Installation of the pipe for the cooling tower water inlet (Right)

As water entered into the cooling tower, the sprinklers installed at the basin as shown in Figure 21 would distribute water evenly along the fill.

Figure 21 Cross-section view of sprinklers and cooling tower fill during cooling tower operation

Although water was evenly distributed within the cooling tower; however, a well-designed fill below the sprinklers was just as important in order to achieve the 5^{o}C “range”. Figure 22 showed a pack of fill used in cooling tower, and the fill was designed in the zig-zag shape to increase the retention time for heat and mass transfer period between air and water.

Figure 22 Front view of the fill (Left) and a pack of cooling tower fill (Right)

Below the fill was a large cold water basin that held the cooled water, a pipe was connected to the centre of the basin for water to exit the tower. The pipe shown in Figure 23 was connected to a large pump which drew water out of the tower and pumped water into a heat plate exchanger to raise the temperature by 5°C to simulate a real case in a cooling plant.

Figure 23 Water piping system used to transport cooling water entering and exiting the cooling tower

With reference to Figure 18, the water main pipe (Figure 23) was connected to a plate heat exchanger as shown in Figure 24 to heat up the water. A by-pass pipe was installed in the system in order to maintain the range temperature at 5°C.

Referring to Figure 18, there were two plate heat exchangers in the setup. The red plate heat exchanger was connected to the cooling tower and the blue plate heat exchanger was connected to boilers with a maximum heating capacity of 4,525 kW (refer to Figure 24). The purpose of this setup was to separate the water circuit between the boilers and the cooling towers as the temperature difference between the two circuits was very significant. As discussed earlier, the maximum water temperature flowing across the tower was 35.5°C, yet in contrast, the boilers temperature was at a much higher temperature that could reach up to 65°C. The fill of cooling tower (where heat transfer between water and air took place) was not designed to operate under such high temperature, so the heated water from the boilers would not be directly fed into the cooling tower and required two plate heat exchangers to transfer heat from the boilers to the cooling towers. The pipes were all well insulated to reduce the loss of heat during the experiment.

Figure 24 Red plate heat exchanger that heats up the water circulating within the cooling tower circuit (Left) Blue plate heat exchanger that heats up the water circulating within the boiler circuit (Middle) Boiler used to generate heat to heat up water for the experiment (Right)

When air was discharged into the environment under a controlled flow rates, as well as under a humid climatic condition, visible plume would occur as shown in Figure 25.

Figure 25 Visible plume during the experiment

4.2 Sensors and Monitoring Equipment

During the experiment, several parameters were recorded, including the Dry Bulb Temperature (DBT) and the WBT of ambient air, air flow rate and water flow rate, as well as discharge air DBT and RH were recorded. Table 4 provides information on sensor type and measurement error. The equipment sensors that are used during the experiments were as shown from Figure 26 – Figure 29.

Table 4 Sensor Information for the cross-flow cooling tower experiment

Manufacturer	Type	Model	Sensor Error
PYROSALES	Platinum Resistance Thermometer Sensor (Air and Water)	TBA	+ 0.03 ~ 0. 05
Rotronic	Temperature & RH Sensor	HydroFlex Tramsitter XB	RH ± 3%
Prova Instruments Inc.	Airflow meter	AVM-01 / AVM-03	+ 0.1 for flow rate unit of m/s
ABB	Electromagnetic Water Flow Meter	MagMaster	Laboratory Testing + 1%

Figure 26 Dry-bulb and wet-bulb temperature sensor at where air is drawn into the cooling tower (Left) Sensors for water temperature at the main pipe (Right)

Figure 27 Monitoring system on DBT and WBT at the inlet of cooling tower and on the water temperature circulating in the "cooling tower circuit"

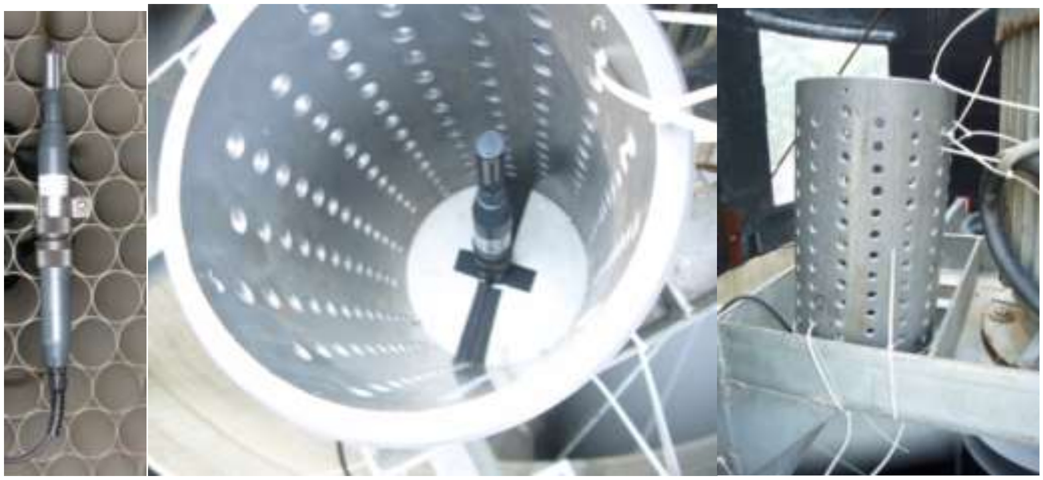


Figure 28 Sensor used for temperature and RH monitoring at discharge of the cooling tower during the experiment

Figure 29 Rotronic HygroFlex - Temperature & RH monitoring equipment (Left) monitoring equipment of the boiler (Right)

During the experiment, data were recorded continuously. In order to obtain reliable results, experiment would only be completed when one hour of stable data were recorded (refer to Table 5 for stable experiment result allowable variance). Once the experimental results became steady, the recorded data were then analyzed.

Table 5 Measurement results allowable variance during experiment

Parameter	Measurement Error
Hot / Cold Water Temperature	±0.05^{o}C
WBT	+0.05^{o}C
Water Flow Rate	±1%
Air Flow Rate	±0.1 m/s

4.3 Results and Discussions

Figure 30 shows the temperature profile of the entire experiment, which shows the WBT remain steady at 25.5^{o}C throughout the experiment and the range temperature is maintained at 5^{o}C. It can also be seen that DBT is not stable during the experiment; however, as the cooling tower relies mainly on the evaporative cooling (the overall efficiency is governed by the differential between circulating water with the ambient air WBT), thus DBT is not a critical parameter that would affect the test of the cooling tower (Havey, 2008, CTI, 2000)

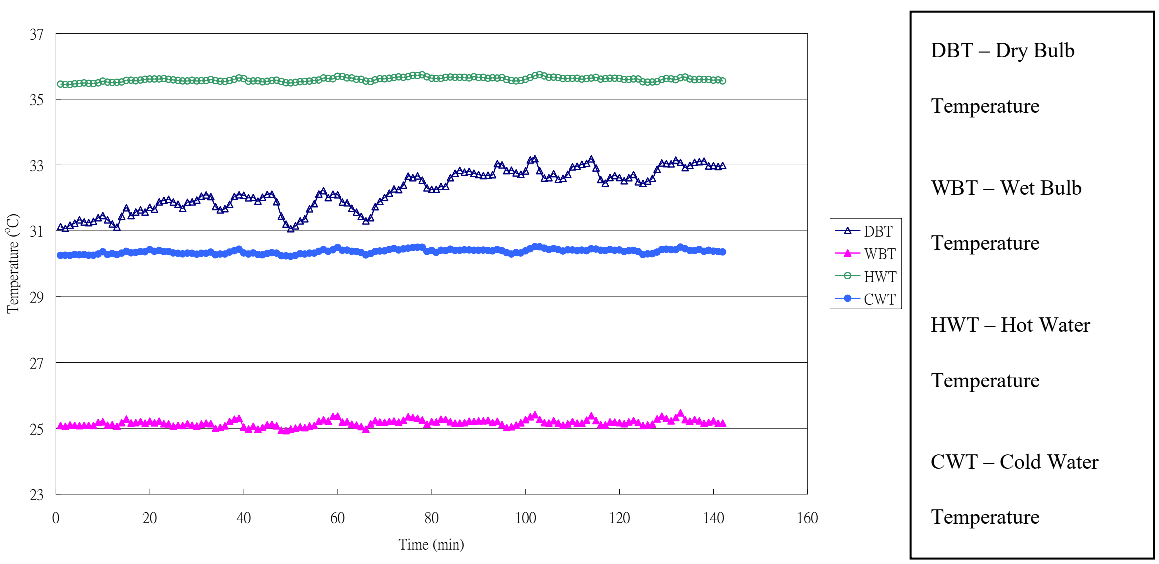


Figure 30 Profile of ambient condition during the experiment.

4.3.1 Result Comparison for Mechanical Cooling Tower

Performance evaluation of a cooling tower was carried out with both the Poppe and the Merkel Approach. The e-NTU approach was not included in this analysis as the calculation showed little discrepancy with the Merkel Approach (Kloppers, 2003).

The discharge air temperature and RH were measured during the experiments, and the data were used to compare with the discharge air condition calculated from both the Poppe Approach and the Merkel Approach to identify which model would be more accurate.

Figure 31 shows the enthalpy calculated with the measurement data, which is used to compare with the enthalpy calculated by the Poppe Approach and the Merkel Approach. The prediction for the air enthalpy at discharge with the Poppe Approach has a smaller discrepancy to the measurement results in comparison to the Merkel Approach (3% variance with Poppe Approach compared to measurement while 5% variance with Merkel Approach compared to measurement). This suggests that the Poppe Approach is more appropriate for performance evaluation, as well as better accuracy and more effective to achieve the objective of plume abatement.

Error band is also included in the analysis as shown in Figure 31. Note however that the error bands for the measurement results are much shorter than the calculated results. This is because the error bands for the measurement results were based on recorded data that involved only the discharge air temperature and discharge air relative humidity, while the error bands for the calculated results are based on the data from airflow rate, water flow rate, recorded water temperature at inlet and outlet points as well as ambient air dry bulb temperature and ambient air wet bulb temperature.

The error on the sensors would give little discrepancy upon the enthalpy of discharge air both in measurement and calculated values. The differences between the calculated and measurement results are very minor as aforementioned, and this difference is due to the fact that calculation approach calculates the discharge air condition at the immediate exit of the cooling tower fill while the measurement is taken at the discharge point that is approximately two meters away from the cooling tower fill. With this additional two meters travelling distance, air may pick up a little more moisture, thus increasing the enthalpy of air, before being discharged into the ambient.

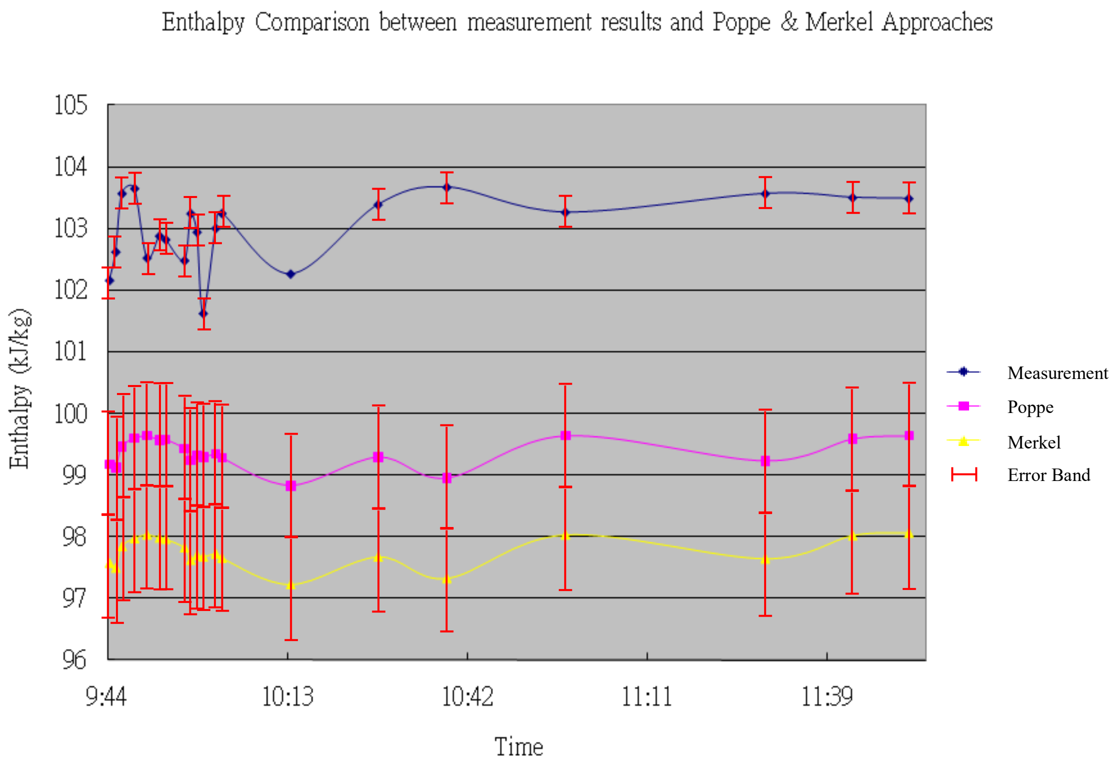


Figure 31 Results comparison on enthalpy of experiment

In computation, finer the grid size represents higher accuracy, but it also indicates that more time is required to carry out the calculation and not always much more accurate than a slightly less fine grid size. It is crucial to balance optimize computation power and time consumption for calculation.

In cooling tower performance calculation, the grid size is the separation of a domain (fill, where heat transfer takes place between air and water) into small sections, and then calculates the evaporative heat transfer between air and water as it travels from one side of the grid to the opposite side of the grid. Finer the grid size meaning higher the accuracy in calculating the evaporative heat transfer between the two media within the domain.

Kloppers (Kloppers, 2003) suggests that the solution domain should be 50 intervals in both directions to reduce the size of grid to optimize speed and accuracy of the calculation. However,

Figure 32 indicates that a grid interval of 20, slightly larger grid than Kloppers proposal, is sufficient to maintain result discrepancy below 0.1%, thus meaning less time consumption in the calculation.

Optimization in calculation speed and accuracy is crucial in building energy evaluation as office building is designed with an enormous amount of cooling capacity (Bosnjakovic, 1965) and very common to have multiple cooling towers installed within the commercial building. There are thousands of data required to be analyze the performance of the cooling tower, and speed for calculation is extremely crucial as quick work-done is demanded by management for their decision making purposes.

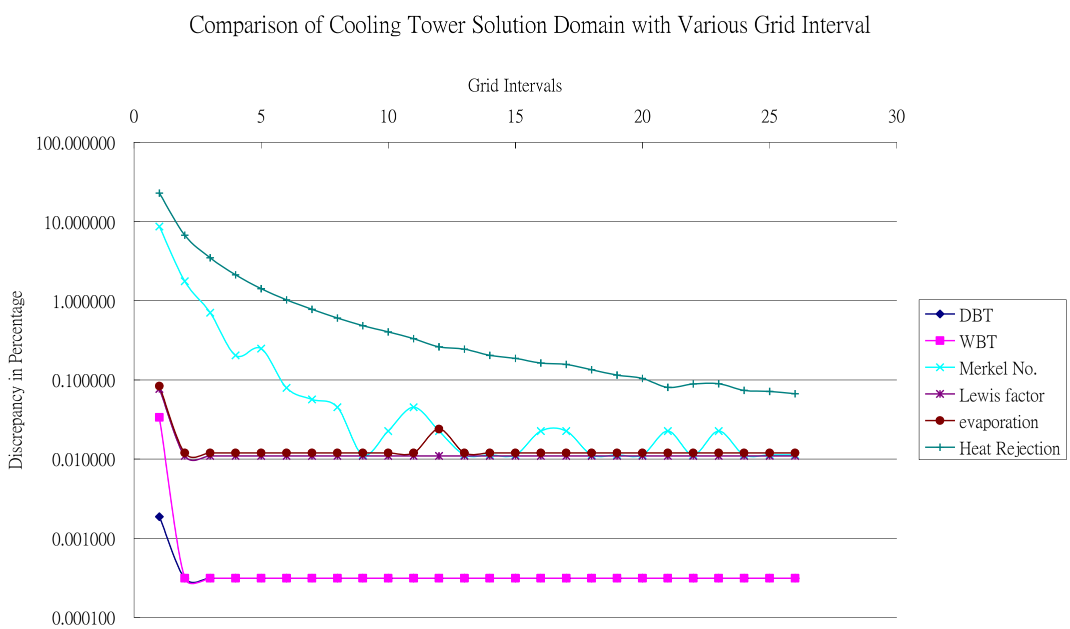


Figure 32 Discrepancy of results at different grid interval

4.3.2 Power Inverse Law Analysis

Regression is an alternative approach for the prediction of equipment behaviour. However, appropriate calibration is required to generate a performance prediction. In this analysis, the power inverse law is proposed.

Power inverse law is used widely in various processes that involve statistical analysis (Allegri & Zhang, 2008, Bardic et al, 2006). It provides opportunities to establish relation between air-water parameters and the heat and mass transfer process of a cooling tower at any specific design criteria. As cooling tower continues to operate, comparison can be made between the new and existing conditions so to determine the "wellness" of cooling tower.

In order to carry out the calibration process, parameters that affect the performance of cooling tower must first be understood. Typically, the parameters that affect the performance of cooling tower is based on intake air WBT, hot water temperature and cold water temperature. However, Roth (Roth, 2001) also suggests that inlet air DBT is another factor that affects the Merkel number from experimental results. With this respect, a calibration equation, Equation (26), is derived based on these four parameters with a correlation coefficient of $r^2 = 1.000$.

$$Me = \frac{1}{(C_1 T_{adb}\big|_y^{\,C_2} + C_3 T_{awb}\big|_y^{\,C_4} + C_5 T_w\big|_x^{\,C_6} + C_7 T_w\big|_{x+\Delta x}^{\,C_8}) + C_9} \qquad (26)$$

$C_1 = 2.67 \times 10^{-3}$

$C_2 = 9.54 \times 10^{-1}$

$C_3 = 75.22$

$C_4 = -7.59 \times 10^{-1}$

$C_5 = -1.44$

$C_6 = 6.02 \times 10^{-1}$

$C_7 = 4.41 \times 10^{-1}$

$C_8 = 1.02$

$C_9 = -7.28$

When there is changes of air and water flow rate are involved, the calibration equation will then be derived as Equation (27) with a correlation coefficient of $r^2 = 0.937$:

$$Me = \left(\frac{1}{(C_1 T_{adb}\Big|_y{}^{C_2} + C_3 T_{awb}\Big|_y{}^{C_4} + C_5 T_w\Big|_x{}^{C_6} + C_7 T_w\Big|_{x+\Delta x}{}^{C_8}) + C_9} \right) \left(C_{10} G_w{}^{C_{11}} + C_{12} G_a{}^{C_{13}} \right) \qquad (27)$$

$C_1 = 1.74 \times 10^{-1}$

$C_2 = -5.14 \times 10^{-1}$

$C_3 = 1.23 \times 10^{-1}$

$C_4 = 1.17 \times 10^{-1}$

$C_5 = -2.76 \times 10^{-1}$

$C_6 = 1.17 \times 10^{-1}$

$C_7 = 3.81 \times 10^{-3}$

$C_8 = 1.11$

$C_9 = 3.30 \times 10^{-1}$

$C_{10} = 3.17 \times 10^{7}$

$C_{11} = -1.08 \times 10^{1}$

$C_{12} = 7.31 \times 10^{-2}$

$C_{13} = 7.72 \times 10$

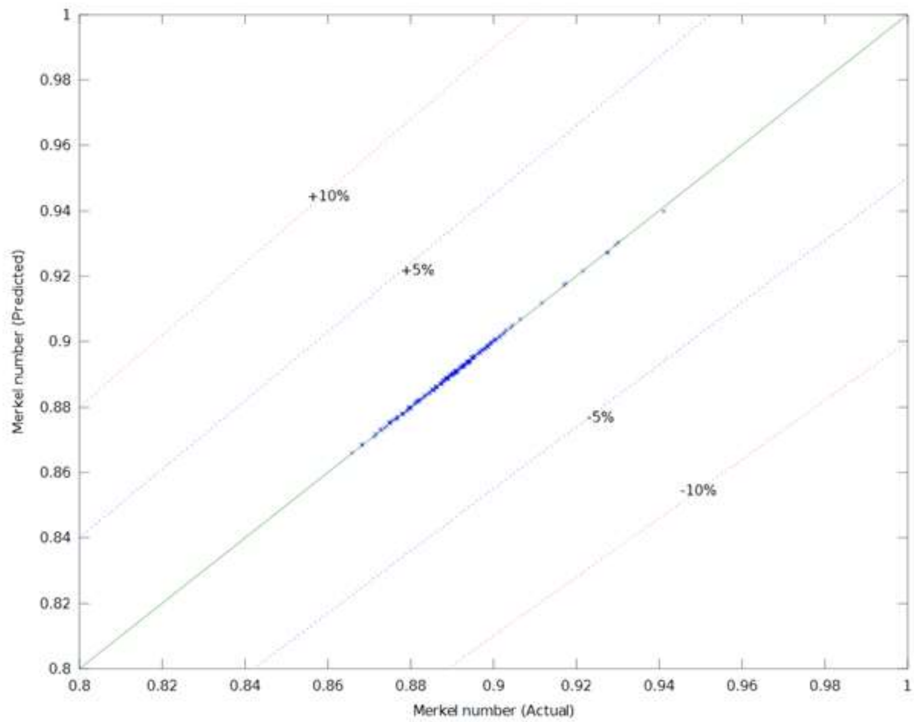
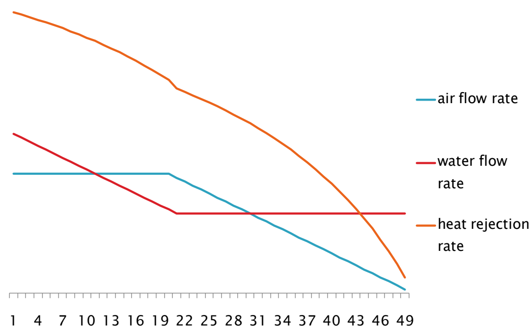


Figure 33 Calibrated results between Merkel Number predicted from Poppe Approach and from experimental results

After calibrating and shows that the measurement results matches with calculation, then the calibrated equation can then be used to estimate the performance of the cooling tower.

Klopper has carried out similar calibration approach to predict the heat rejection performance of a fill. In order to verify the results of the calibrated equation, the calculated results from this study is compared with Klopper's work. As can be seen in Figure 34 the changes in heat rejection rate of the two cases follow a similar pattern, thus this shows that the calibrated equation used in this study is accurate and can be used to predict cooling tower performance at different climatic and loading conditions.



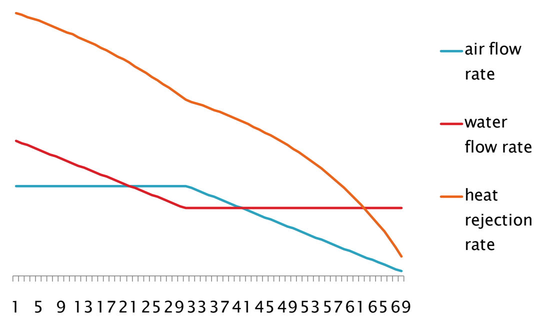


Figure 34 Heat rejection rate with the change in L/G ratio with regression approach (Left) and Kloppers's experiment (Right)

4.4 Summary

In this study, thermal performance experiment of a real cooling tower to cool 350m^3/hr with a range temperature of 5^{o}C was carried out to provide comparison between the Poppe Approach and Merkel Approach. Enthalpy, which was calculated from the DBT and RH, was used as a reference during the validation process. Both approaches were close to the measured result, but the Poppe Approach shows a smaller discrepancy and hence more accurate.

Although the Poppe Approach is more accurate, but longer calculation time is required due to the complexity of the calculation approach. With this respect, grid interval was set at 20 in order to optimize accuracy and calculation speed as the grid size would show a result discrepancy of less than 0.1% even with more grids are available.

A calibration process was also developed to further enhance the cooling tower performance calculation. The empirical equations derived have a correlation coefficient of r^2 = 1.000 for constant air and water flow rate and r^2 = 0.937 for variable air and water flow rate. The accurate empirical equations can be used for cooling tower performance prediction, and possible to determine the "wellness" for cooling tower once new and existing conditions are compared.

Chapter 5 – Environmental Chamber Study of Wet Plume of Cooling Towers

5.1 Visible Plume in HK

Although cooling tower is effective in heat rejection, there are also disadvantages with this equipment. One major concern upon cooling tower is the “visible” plume phenomenon. As fresh air is drawn into the cooling tower, the direct contact between air and water will cause evaporation to occur during the heat exchange process and with air becomes high in moisture level. If ambient environment is very humid, moist air discharged from the cooling tower will have a high possibility to become visible. Visible plume is considered as a pollutant according to the Air Pollution Control Ordinance (APCO) established by the Environmental Protection Department (EPD) of Hong Kong Government (EMSD, 2006).

Visible plume is very common in Hong Kong during spring with the highest environmental RH reaching up to 98%. Condensation as mist in the cooling tower system is of great impact on both human and equipment health. In terms of health, it is important to realize that cooling tower is operating between 20^{o}C to 45^{o}C, at which the water temperature range is desirable for bacteria to grow, namely the Legionella [Legg, 1991, Hyland et al, 2007]. Hong Kong official hospitality records also showed a significant increase in cases of Legionnaire’s Disease since 2000 with the increasing number of cooling towers installed within the urban city [DoH, 2010].

Beside moist air, drift (water droplets) is another factor that contributes to the visibility of plume. Small water droplets in diameter ranging from 0.1mm-1.0mm may flow along with the airflow and exit cooling tower even with the availability of drift eliminators [Meroney 2008, Valley, 2009]. Since Legionella can survive in droplets of diameter ranging from 1-15μm [Percival et al, 2004, Hart & Makin, 1991], the more severe the visible plume means the further the distance these contaminated droplets may travel when droplets. Condensation of moist air also means the growth of water droplet while airborne, providing more nutrients and space for Legionella to grow. As droplets grow in size, the impact of gravitational power on the droplets also increases and enforces them to drop and may fall upon ground level. This creates a great health hazard if the droplets are dropped upon a crowded area within an urban city.

Chemical treatment can provide immediate disinfection for the cooling towers, but it is not able to ensure the Legionella in the system is kept to the minimum until the next sample test is carried out. While that is the case, over-dosing of chemical is almost inevitable yet at the same time not desirable, as water droplets discharged from the cooling tower may contain chemical that can be harmful to human health.

While droplets escaping from the cooling tower may contain pollutants or chemicals that affect human health, it is also accountable for the unnecessary water loss in the system. Lucas suggests that most electronic system failure is due to drift loss from cooling tower due to corrosion upon equipment, piping and structural steel (Lucas, 2009).

Nonetheless, visible plume is the product of moist air discharged from cooling tower, and has an adverse impact on the community in terms of environmental impact, human health and equipment performance. Although the Poppe Approach is a very effective numerical model for “visible” plume detection, yet it is not able to identify the spread of plume within a humid environment.

In order to identify the effect of plume visibility, the behavior of plume in terms of the route of flow and spread, as well as the severity, must be understood in carrying out the environmental impact studies. With this respect, a study of plume visibility within a testing chamber is carried out. The testing chamber study is expected to provide insight for the “visible” plume phenomena under variation of climatic conditions at low wind condition. In order to further justify the accuracy of the “visible” plume behavior, Computation Fluid Dynamic (CFD) is also adopted to simulate the visible plume phenomena and compared with the experimental result as shown in Section 5.3.

Michioka (Michioka et al, 2007) has carried out a visible plume study with the use of tracer gas in a wind tunnel. The proposed approach is one of the indicative analyses to identify the “visibility” of plume, but is limited by the uncontrollable climatic condition for a humid environment which determines the size and severity of visible plume. In this thesis, a testing chamber is designed to create a range of artificial climatic condition with high humidity that is possible to show the severity of plume under different scenarios. The purpose is to further identify how the visibility of plume can be abated.

Previous studies have been carried out for the analysis of visible plume abatement in Hong Kong, and suggested that for plume to become visible, the minimum RH will have to be at a 90% (Xu et al, 2007). Following the same approach with the 2009 meteorological information in Hong Kong, it is highly probably that 826 hours during normal working period will have plume to occur, which occupies 25% of the time for the entire year as shown in Figure 35. Base on this assumption, the chamber is designed to provide an artificial condition with RH of 90% or higher and possible to reach up to 98%.

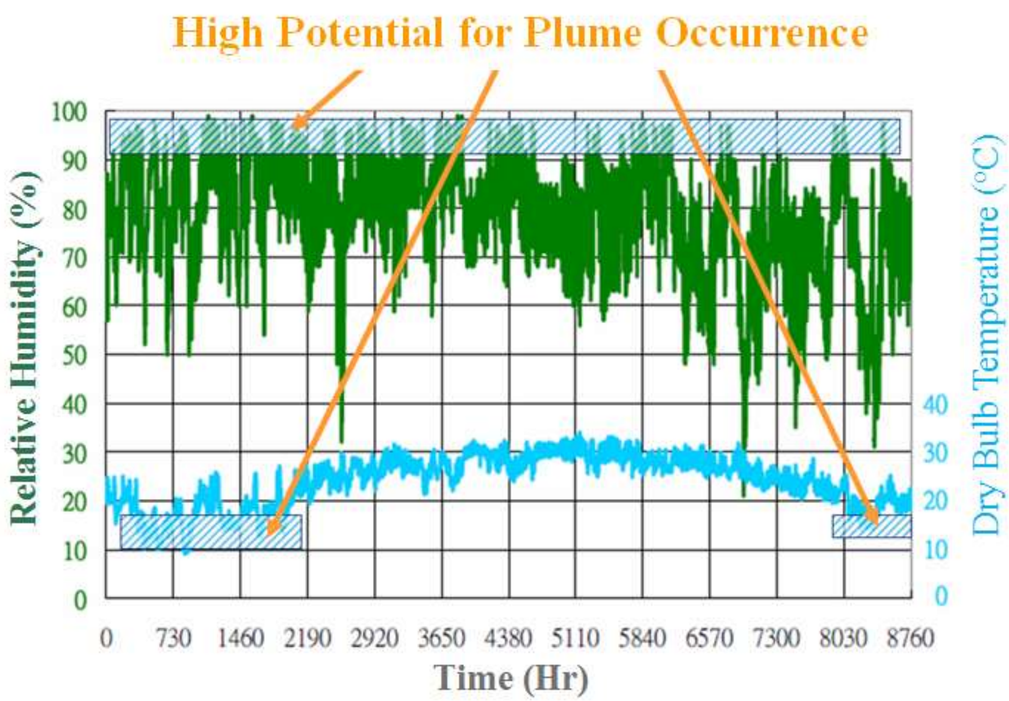


Figure 35 Region of possible plume visibility in Hong Kong with 2006 meteorological information on ambient air conditions

5.2 Artificial Environmental Chamber Design

5.2.1 Discussion on the Artificial Environmental Chamber Design

Visible air from a cooling tower can be very severe and can be classified as a pollutant. Therefore, small droplets discharged along with the air from cooling tower can affect civilians in close proximity, and visible plume can cause a serious concern upon the society with respect to public health. Figure 36 shows visible plume can be spotted in the public and how it may become a naissance to the public.

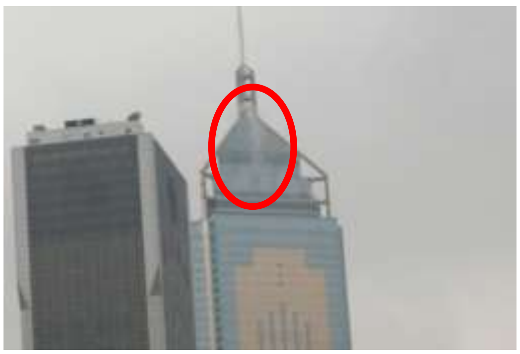


Figure 36 Visible plume discharged from a cooling tower in tall building and airport

Although there is a necessity to study the flow pattern of the visible plume at different prevailing wind conditions. However, there are several limitations with a real case experiment, which includes:

- The impossibility to control the environmental condition, such as ambient dry-bulb and wet-bulb air temperature, wind speed and wind direction.
- The high cost in undertaking experiments with a real sized cooling tower
- The difficulty to monitor and taking measurement of the visible plume

Due to these difficulties, visible plume experiment is usually undertaken in a scaled model. Michioka has undertaken a study on plume by releasing tracer gas from a scaled jet in a wind tunnel (Michioka et al, 2007). However, the tracer gas experiment can only simulate the flow pattern of cooling tower discharge but not able to identify the visibility of the plume as the environmental condition cannot be controlled.

In order to study the visibility of plume under different environmental conditions, a testing chamber was designed to create several artificial environments and hence the severity of plume at different climatic conditions.

Figure 37 shows the water boiler that was used to humidify air in the artificial environment to create humid testing artificial environment.

The chamber was 2.5m wide, 6m long and 3m high as shown in Figure 37. The jet (refer to Figure 38) at the centre and bottom of the chamber was designed to discharge moist air simulating the discharge air condition of a cooling tower. The diameter of the discharge jet was 250mm and locating 140mm above the base panel, and the scale ratio between a real cooling tower and the discharge jet of the chamber was 1:10. It must be noted that the minimum distance from the centre of the jet to the side of the wall was kept at a distance ten times the radius, which allowed the wall acceleration effect to be kept to the minimum in order to minimize the its impact on the flow pattern of the plume.

Figure 37 Water boiler that controls the moisture content of the discharge air inlet (Left) testing chamber for scaled cooling tower visible plume test (Right)

5.2.2 Design of Discharge Jet

The discharge jet was scaled down by a factor of ten as aforementioned and with a maximum design velocity of 7.4m/s. The discharge jet was designed to place at the centre of the testing chamber to maintain the same pressure profile amongst the left and the right side of the chamber. The dimension and discharge velocity of the jet were designed by adopting the similarity scaling law in order to maintain a steady and scaled discharging condition compared to the actual discharge of a cooling tower.

Although the mass flow rate for the discharge was scaled down along with the diameter, the stack Reynold's number (Re_s) of the discharge jet was calculated and maintained at approximately 9.65×10^4 and was of two orders of magnitude lower than an actual cooling tower discharge, which could affect the flow pattern of the visible plume. Sharma et al and Uehara (Sharma et al, 2005, Uehara et al, 2003) experienced similar situation where there was a difference in Reynold's number between the wind tunnel test and an actual case. However, Contini et al (Contini et al, 2009) stated that the difference in the stack Reynold's number would only be critical when there was insufficient momentum and buoyancy effect to avoid entrainment in the stack wake. Given that there was no other object within the chamber that could create any wake effect, and that the size of the testing chamber was relatively larger compared with the discharge jet, it was logical to assume that the difference in stack Reynold's number would not have any impact in the experiment.

The design drawing of a cross-section detail of the discharge jet is shown in Figure 38.

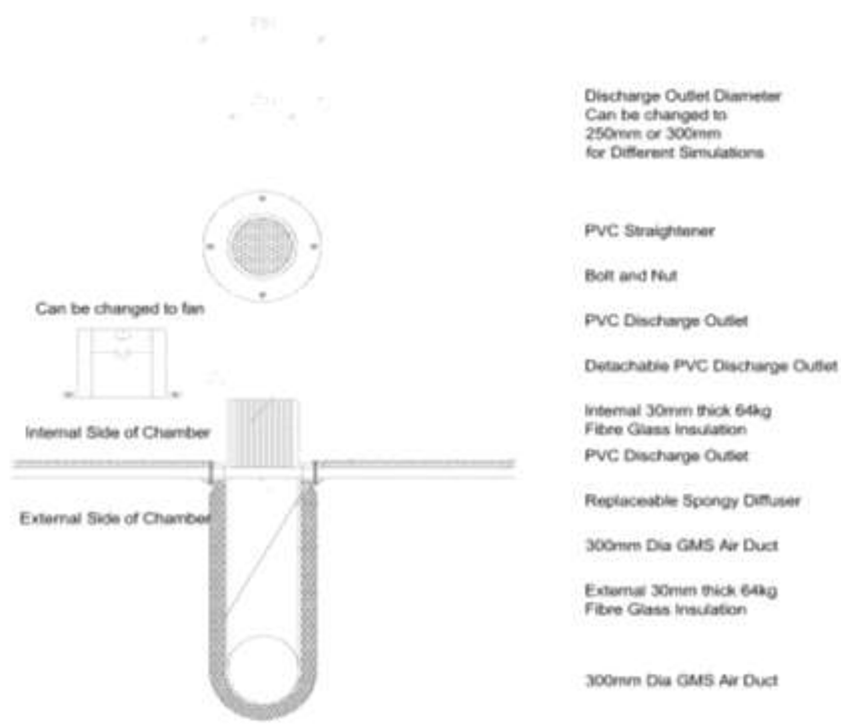


Figure 38 Design drawing of the discharge air jet in cross-section view (Left)

Since the testing chamber was designed with the consideration on change in thermal condition, the Richardson number was also evaluated. This dimensionless number was the representation of the ratio of potential energy and kinetic energy of the flow. In the design, the Richardson number (Ri) was approximately 0.02 from the immediate discharge point location, which showed that the buoyancy impact was negligible in the experiment and aligned with an actual cooling tower performance.

The jet discharge was designed to achieve and then to maintain temperature within 20 – 38^{o}C and RH within 85 – 100%. In the design, a PAU was selected that could provide a maximum air flow rate of 1,000m^3/hr and installed with a fan capable of a rotating speed of 920rpm with a rated power capacity of 1.1kW.

In order to achieve the design temperature range, the PAU was able to achieve a cooling capacity of 13.9kW and the sensitive heating capacity of 5.8kW. As for the humidity ratio, an electric heater with a heating power of 12.0 kW was installed in the humidifier with the humidifying capacity of 45 kg/hr. Left figure of Figure 39 showed the humidifier installed below the testing chamber to humidify the air passing through the PAU. Air would only enter through the PAU once, meaning that the conditioned air would not enter the testing chamber until the chamber and the discharged air condition were appropriate for experiment. Therefore, an opening was required to allow air to exit the testing chamber as shown in the right figure of Figure 39.

Figure 39 Humidifier that controls the moisture content of the discharge air jet (Left) Opening to discharge humid air while stabilizing discharge air condition (Right)

In order to control the air flow route of the conditioned air from the PAU, a pneumatic damper was installed below the discharge jet. The damper would keep the conditioned air from the PAU from entering the testing chamber while preparing the condition of the jet for any specific experimental condition. Once the artificial condition and the jet discharge condition was at the same condition as designed for experiment, the damper would open and allow moist air simulating cooling tower discharge to enter the chamber.

5.2.3 Design of the Artificial Environment of the Testing Chamber

A PAU was selected to simulate a discharge air condition an AHU was selected to condition the artificial environment with temperature within the range between 12 – 28^{o}C and RH between 60 – 98%.

Steady temperature of the chamber was maintained but with large power consumption would be required as the chamber is of a significant size. The cooling capacity of the AHU was 17.7kW and the sensitive heating capacity was 11.8kW. In order to maintain the desirable RH, an electric heater with the heating power of 6kW and a humidifier with the humidifying capacity of 10 kg/hr were installed.

The AHU used chill water to achieve cooling process, which the compressor of the AHU and the chill water container are as shown in Figure 40. The chill water was cooled by the refrigerant circulating within the system, which heat was exchanged at the bottom of the chill water container via indirect cooling. The refrigerant would then be cooled by air to release the heat gained from the chilled water.

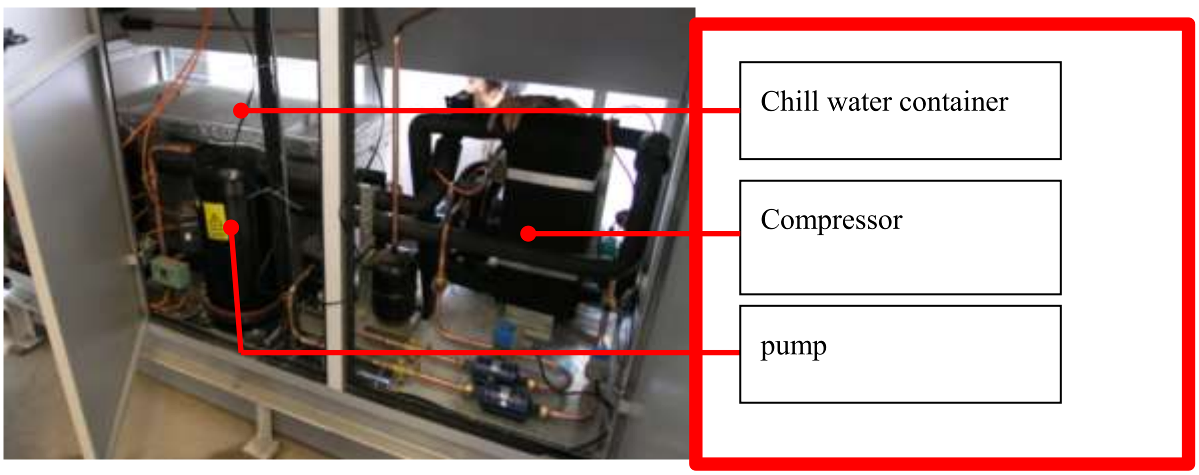


Figure 40 AHU system adopted to control the artificial environment of the testing chamber

As chilled water was cooled by the refrigerant, air recirculating within the testing chamber would then be cooled by the chilled water. The design air flow rate through the AHU was 3,700m^3/hr, and circulated within the testing chamber with a fan of 920rpm rotation speed and a design power capacity of 1.5kW.

As the objective of the testing chamber is to evaluate the shape of the visible plume within a range of controlled artificial conditions, careful considerations must be taken. In the design of the testing chamber, there are two major concerns. The first major concern for the experiment is whether if the humid air from the discharged jet will have a dramatic change on the artificial environment once discharged.

In order to ensure the control of the chamber environmental condition, the Air Change Rate (ACH) between the chamber and discharge jet during the experiment must be high. The equation that is used to calculate the ACH in the chamber with a jet discharging saturated air at 7.4 m/s is as shown below.

$$ACH = 3600\frac{q}{V} \tag{28}$$

where q = Saturated air discharging into the chamber (m^3/s)
V = Volume of the controlled artificial environment of the testing chamber

With the jet discharging saturated air at 7.4m/s, the ACH within the chamber is approximately 30 and is sufficient in maintaining a stable environmental condition during the experiment.

Another concern of the testing chamber is how to achieve the desirable temperature and RH within the testing chamber when preparing for the experiment.

Figure 41 shows air flowing through multiple of ducts (one of them is behind the duct work that leads to the opening to discharge the relative hotter and more humid air) from the bottom from the AHU into the large testing area of the testing chamber.

Figure 41 Vent that transports treated air into the testing chamber

The testing area is separated into two sections by perforated panels, which the lower section is as shown in the left figure of Figure 42. The purpose is to separate the testing area by creating a region below the perforated panels for air to mix before entering the testing area of the chamber above the perforated panels.

A total of eight centrifugal fans are installed on the perforated panels, which drew air from the lower section into the upper section of the testing area. These centrifugal fans (refer to in the right figure of Figure 42) are selected to push air above the perforated panels gently and in all directions. These fans are designed to operate in low speed and will not cause any significant impact on the turbulence and the airflow within the chamber throughout the experiment.

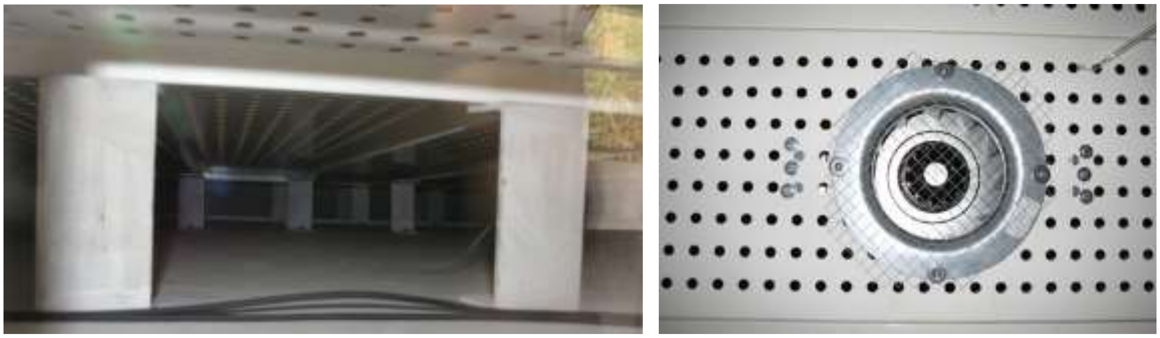


Figure 42 Lower section of the testing chamber (Left) Centrifugal fan at the perforated panels (Right)

A total of eight centrifugal fans are installed on the perforated panels, which drew air from the lower section into the upper section of the testing area. These centrifugal fans (refer to Figure 42) are selected to push air above the perforated panels gently and in all directions. These fans are designed to operate in low speed and will not cause any significant impact on the turbulence and the airflow within the chamber throughout the experiment.

5.2.4 Design for No-Wind Condition

With the above configuration, the artificial environment and the discharge condition can be simulated. The chamber is capable to carry out a no-wind condition, where there will only be saturated air (simulating cooling tower discharge) discharging into the artificial environment.

Figure 43 shows the operating arrangement of the testing chamber under no-wind condition; air will be diffusing upward using the small centrifugal fans during preparation to prepare an artificial environment.

In addition, perforated panels were also installed at the top of the testing chamber to allow air to escape from the top via diffusive manner prior and circulates within the testing system .

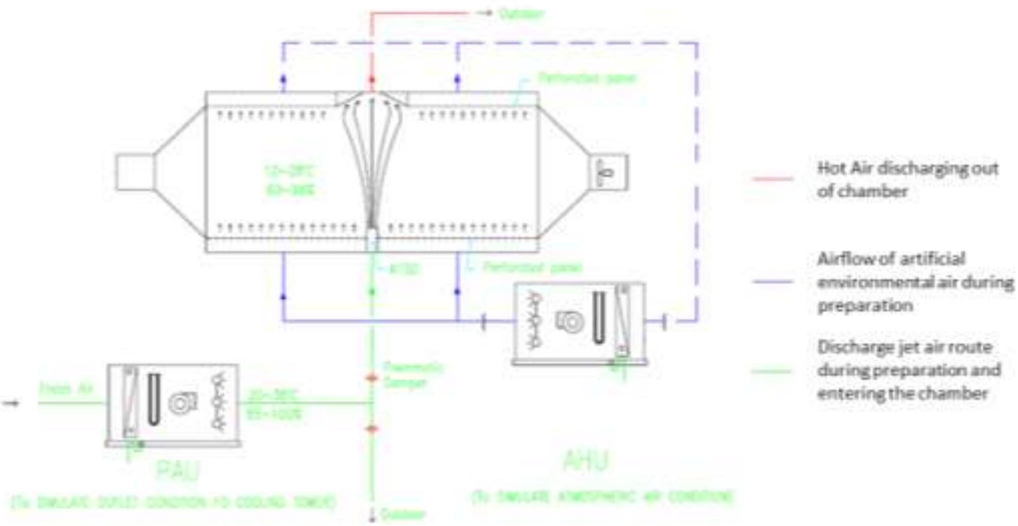


Figure 43 Schematic diagram of a testing chamber during no-wind condition

Thermocouples were mounted at different height vertically above the discharge jet and connected to metallic wires as shown in Figure 44. These (K-Type) thermocouples were used to measure the change in temperature during the experiment.

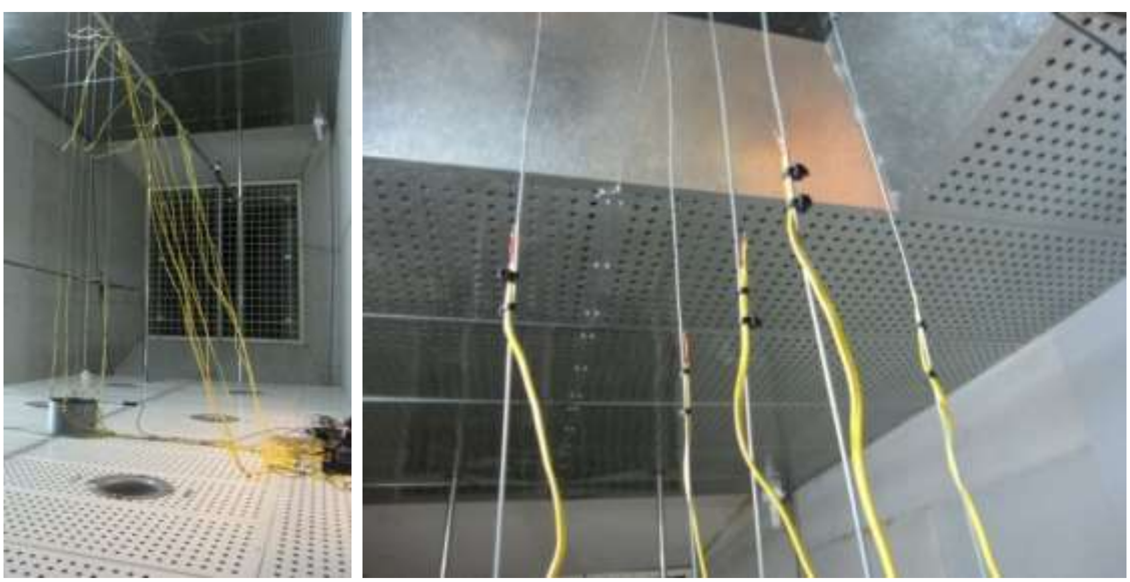


Figure 44 Experimental setup above the discharge air

There were a total of nine wires placed vertically upward, which four were placed at the most outlier position of the discharge jet, four at the midpoint of the radius in four directions and one at the centre of the discharge jet.

The locations of the sensors as described are illustrated in Figure 45.

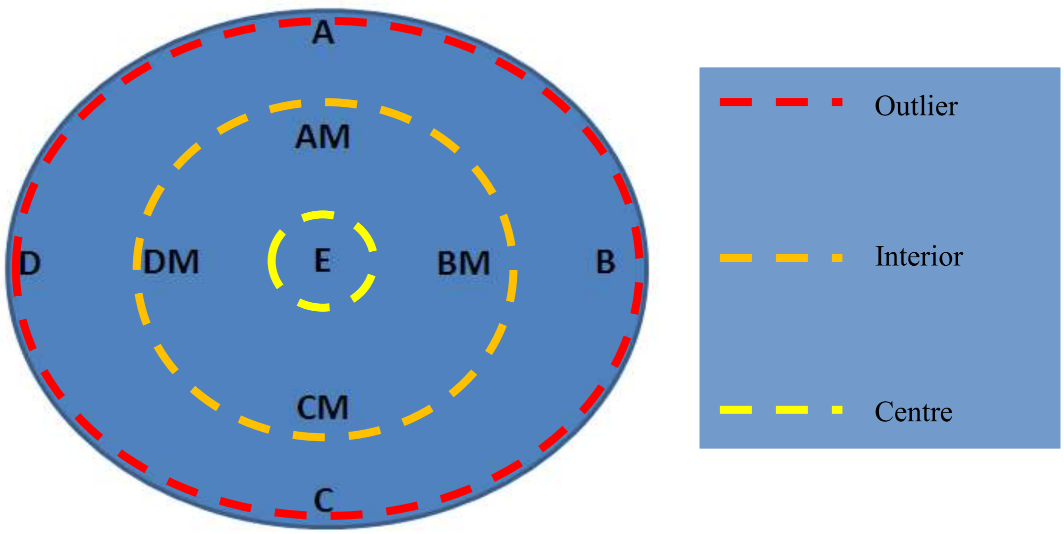


Figure 45 Locations of the sensors (Top View)

Selection of the wires was important in the experiment as these wires and thermocouples could not be too large as it would affect the pattern of the plume. The metallic wires used were approximately 1mm in diameter, this would mean that the combination of the wires all together would not cover the horizontal surface of discharge jet by more than 5% in area; hence there should be no major impact on the discharge flow pattern. Given that the wires were high in strength and were properly wired up, measurement point would remain in the same position during the experiment.

The original intent of the experiment was to mount thermocouples at specific heights of 0.0m, 0.3m, 0.6m, 0.9m, 1.2m, 1.5m and 1.8m above the discharge jet, in order to collect as many data as possible. However, as there were only 20 thermocouples available, the experiments were carried out three times with different sensor formations at the same artificial environmental condition.

Formation of the sensors locations are shown in Figure 46.

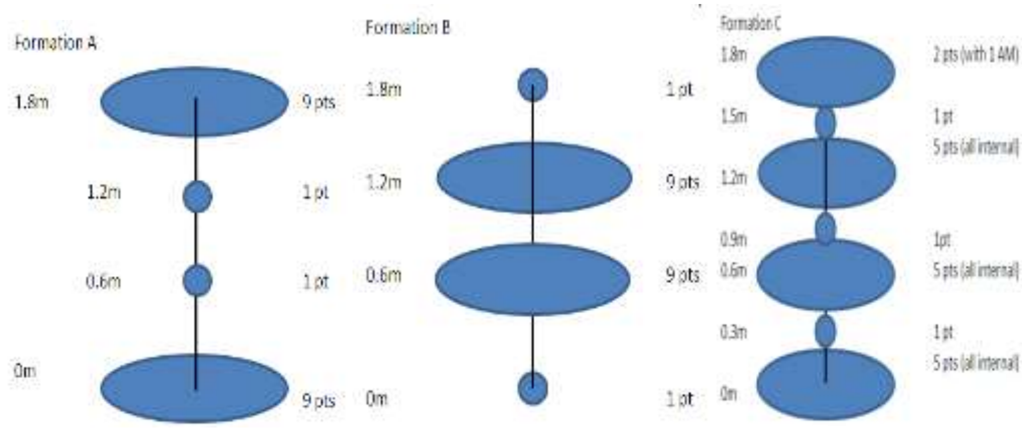


Figure 46 Sensor formations for the experiment of the same artificial environmental condition for no-wind condition

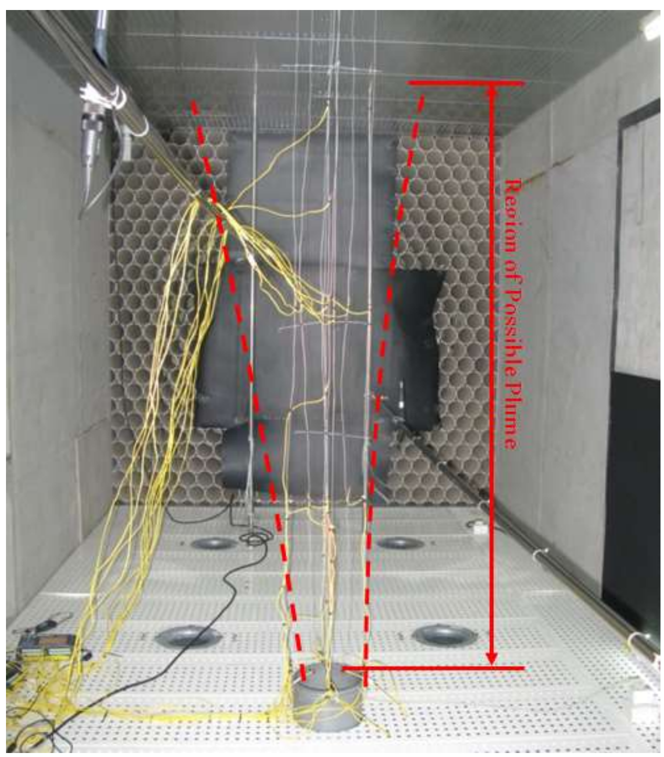


Figure 47 Flow pattern of visible plume at no-wind condition

In order to identify if the flow pattern of plume was obstructed by the wires and the thermocouples, a trial run was carried out. Figure 47 showed that the plume was abound within the high-lighted region and disperse, which indicated that the metallic wires and the thermocouples would not affect the flow pattern as moist air simulating cooling tower was discharged into the testing chamber.

5.2.5 Design for Cross-Wind Condition

In this thesis, only the no-wind condition is simulated due to resource availability. However, the testing chamber is also capable to carry out experiments with cross-wind, the preparation procedures is the same as the no-wind condition. However, when the experiment commences, a large fan (fan diameter >2.5m) install at one side of the testing chamber will be switched on to create a cross-wind airflow as shown in Figure 48.

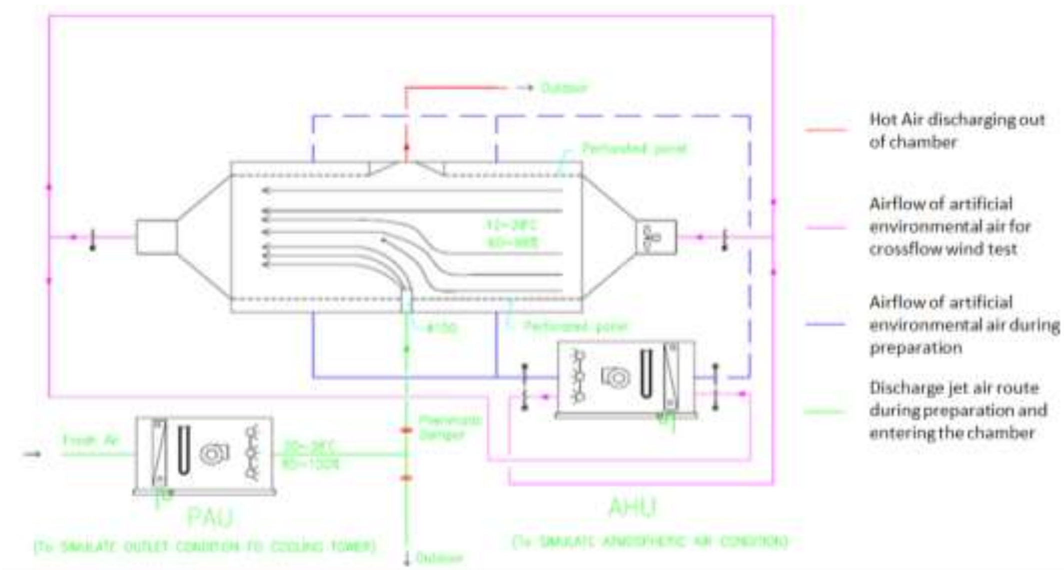


Figure 48 Schematic diagram of a testing chamber during cross-wind condition

The cross-wind airflow will be at the same temperature and relative humidity as the artificial chamber as the ducting connected to the chamber as shown in the right figure of Figure 49 is filled with air of same temperature and RH as the chamber itself during preparation of the experiment.

However, due to the limitation of space available for the testing laboratory, the air-duct has several turning points; which when air flows along the duct, high turbulence will be expected and increase the potential of unbalance air flow and at different air velocity within the testing chamber.

In order to reduce the turbulence of cross-wind air during the experiments to achieve fair distribution of cross-wind airflow and velocity, honeycomb that is 0.5m in length and 0.05m in radius is arranged at the cross-wind intake point. The left figure of Figure 49 shows the honeycomb of the testing chamber. The velocity of the cross-wind is measured with a maximum velocity of approximately 5m/s.

Figure 49 Main air-duct for air circulation (Left) Front view of the circular honeycomb (Right)

5.2.6 Experimental Instruments

The experimental setups for both the no-wind condition and cross-wind conditions have been described, and this section is to provide description on the detail of the equipment used to measure and to record the experimental data.

Two types of sensors are adopted, which one of sensors is the thermocouple as aforementioned to measure the change in temperature during the experiment with sensor error of $\pm 0.5^{o}$. The recorded temperature values are fed into midi logger as shown in Figure 50.

Another type of sensor uses in the experiment can measure both temperature and RH, and it is called Rotronic Hygro Flex. This sensor is highly accurate with temperature error of $\pm$ 0.03^{o}C and RH error of $\pm$ 3%. Figure 50 shows the Rotronic Hygro Flex with the dimension of 0.2m in length and 0.01m in radius.

Figure 50 GL450 midi LOGGER (Left) Temperature / RH sensor (Right)

In the hope to collect data to show the possibility changes in RH along the discharge air path while does not disrupt the flow pattern of discharge air due to its large in size compare to the jet horizontal area, one Rotronic Hygro Flex is mounted above the discharge jet and the highest position of the chamber to collect data for further analysis.

Another use of this sensor is to monitor the internal environment during the experiment, which one Retronic Hygro Flex was located approximately 1.5m away from the jet (at leeward side of the chamber), 1m above the perforated panels, and 0.5m away from the centre of the testing chamber. The sensor is located far away from the jet to ensure it has no effect upon the flow pattern of the air discharged into the environment.

Data retrieves from the sensors can be read from the monitoring instruments as shown in the left figure of Figure 51, and these data will also be fed into a computer that controls the performance of AHU and PAU. Changes in the boundary condition can be set through the control panel as shown in the right figure of Figure 51

Figure 51 Monitoring instruments for the Rotronic Hygro Flex (Left) Control panels of the testing chamber (Right)

5.3 CFD Simulation 3D Model

This section describes the 3D Simulation model to show how CFD is validated with the results of the testing chamber. The model would then be used to carry out simulation shown in Section 7.3.

The first phase to conduct a CFD simulation was to construct a 3D model of the same dimension as the internal environment (2.5m wide, 6m long and 3m high) of the testing chamber, which is as shown in Figure 52 with the inlet and outlet points for no-wind condition.

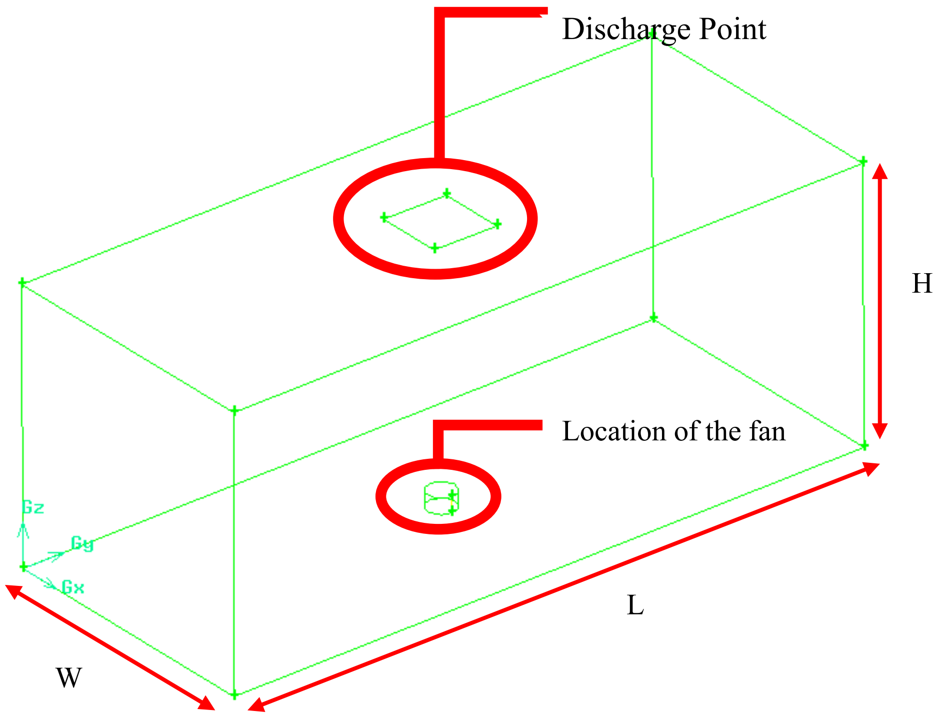


Figure 52 3D model of the artificial chamber for CFD simulation

The 3D model was constructed with the use of a program – Gambit, and tetrahedral mesh was used to create meshes within the internal environment of the testing chamber. Tetrahedral mesh was used as it is easier to mesh with cylindrical object within the domain and it could reflect better on the airflow pattern in CFD simulation.

Grid is defined as smaller shapes formed after discretization of a geometry domain, and grid size is crucial to the accuracy of the calculation (Zhang & Yu, 2013). However, finer grid size means more computation power, and it is important to optimize the grid size and computation power. Figure 53 shows the 3D model used for CFD simulation, and the total number of meshes for this 3D model is 700,000.

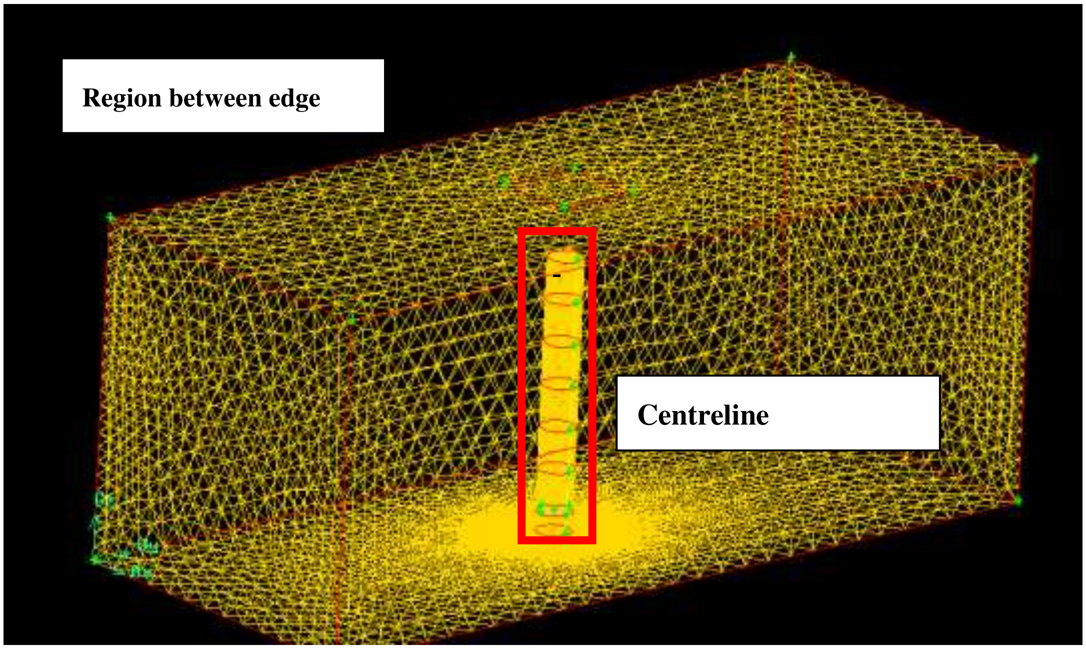


Figure 53 Variation of mesh resolution of the 3D model

5.3.1 CFD Mathematical Model

5.3.1.1 Mathematical Model of Turbulent Model

With this CFD simulation, literature survey has been carried out to select the appropriate turbulent model. According to Meroney, standard k-ε turbulence model is satisfactory for cooling tower simulation (Meroney, 2008) and it is used to compare the simulation results with the experimental results.

Standard k-ε turbulence model is developed by Launder and Spalding (launder & Spalding 1972) and is valid for flow that is fully turbulent and with negligible molecular viscosity. This model consists of two major parameters, which are the turbulence kinetic energy (k) and the turbulence dissipation rate (ε).

The standard k-ε turbulence model is a two equation model that describes the turbulence kinetic energy, k, and the turbulent dissipation, ε. The equation that describes turbulence kinetic energy is as shown in Equation (29)

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(u + \frac{u_t}{\alpha_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k \quad (29)$$

and the turbulent dissipation is as shown in Equation (30)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(u + \frac{u_t}{\alpha_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_k \quad (30)$$

where

G_k – generation of turbulence kinetic energy via the mean velocity gradient

G_b – generation of turbulence kinetic energy via buoyancy

Y_m – contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

σ_k – turbulent Prandtl numbers for turbulence kinetic energy

σ_j – turbulent Prandtl numbers for turbulence dissipation

$C_{1\varepsilon}$– constant

$C_{2\varepsilon}$– constant

$C_{3\varepsilon}$– constant

C_μ – constant

In fluent, the constants for a standard *k*-*ε* turbulence model are specified as below

$C_{1\varepsilon}$= 1.44, $C_{2\varepsilon}$=1.92, C_μ = 0.09, σ_k = 1.0 , σ_j = 1.3

As for constant $C_{3\varepsilon}$, it determines the buoyancy effect, and thus determines the kinetic dissipation. In Fluent, this constant is calculated based on the equation proposed by Henkes (Henkes et al) as shown in Equation (31)

$$C_{3\varepsilon} = tanh\left|\frac{v}{u}\right| \quad (31)$$

where

v – component of the flow velocity parallel to the gravitational vector

u – component of the velocity perpendicular to the gravitational vector

This means that if $C_{3\varepsilon}$ is 1, buoyancy dominates the airflow pattern, and vice versa when $C_{3\varepsilon}$ is 0.

5.3.1.2 Mathematical Model of Relative Humidity

RH is another factor that is simulated in this study. With fluent, RH can be simulated with the use of calculation for species transportation by identifying the level of moisture content within air.

RH is the amount of moisture that air can "hold" at a specific temperature, and is defined as the ratio between the current absolute humidity level to the highest possible absolute humidity level. RH is measured in percentage, and when RH reaches 100%, air will be considered as saturated condition (Refer to Figure 2 for 100% RH at different DBT).

With fluent, RH is calculated based on the ratio of partial pressure of air over the saturation of a water vapor at the temperature of air mixture. The calculation is carried out by Equation (32)

$$ln\left(\frac{p}{p_c}\right) = \left(\frac{T_c}{T} - 1\right) \times \sum_{i=1}^{8} F_i\left[\alpha\left(T - T_p\right)\right]^{i-1} \quad (32)$$

where

ρ_c – 22.089 MPa

T_c – 647.286°K = 374.186°C

F_1 – -7.4192420

F_2 – 2.9721000 x 10^{-1}

F_3 – -1.155286×10^{-1}

F_4 – 8.6856350×10^{-3}

F_5 – 1.0940980×10^{-3}

F_6 – $-4.3999300 \times 10^{-3}$

F_7 – 2.5206580×10^{-3}

F_8 – $-5.2186840 \times 10^{-4}$

α – 0.01

T_p – $338.15^{o}K = 65^{o}C$

5.3.1.3 Boundary Setting for Experiment & CFD Simulation

Visible plume occurs when RH within an environment is higher than 90%. With the analysis of the Hong Kong climatic data in 2009, there are a total of 1,288 hours that RH exceeding 90%, in which 501 hours occurs during spring. This means that it is highly probable that the period that visible plume issue is most severe during spring. Therefore, environmental conditions that can well represent spring are considered for the experiments, which the conditions are as shown in Table 6.

Table 6 Artificial environment condition of the experiments

Trial	Dry Bulb Temp	RH
1	$17.7^{o}C$	91.1%
2	$16.6\,^{o}C$	91.5%

After selecting the environmental conditions, it is necessary to calculate the discharge air conditions that discharged air will cause visible plume.

In order to realistically show the plume occurrence condition, calculation was carried out to calculate the discharge air condition with a real cooling tower under the aforementioned environmental conditions.

The cooling tower model selected for the experiment was a cross-flow cooling tower with the design water flow rate of 350m^3/hr and an air flow rate of 313,000m^3/hr. The enter water temperatures and the leaving water temperature were as design with 37^{o}C and 32^{o}C respectively. Poppe Approach was used to calculate the discharge conditions based on the environmental condition and the cooling tower operating condition.

Table 7 shows the discharge condition for Trial 1 and 2 of the experiment and the CFD simulation.

Table 7 Discharge condition of the discharge jet

Trial	Dry Bulb Temp	RH
1	23.0^{o}C	99.5%
2	22.3 ^{o}C	100.0%

However, CFD simulation requires more input parameters to reflect more of the actual condition of the experiment. These parameters include:

- Wall

  As the testing chamber was designed to be covered by good insulation materials, there would be no heat lost through the walls. Therefore, walls were set as adiabatic to represent this phenomenon.

- Perforated Panel

  The perforated panels were recorded with a lower velocity (0.3m/s) entering the testing chamber to maintain a steady artificial environment during the preparation. However, as the holes of the perforated panels were very small and made it difficult to construct the 3D model. Therefore, the entire perforated panel was considered as a plane surface and set with an intake velocity of 0.3m/s.

- Outlet at top of the testing chamber

  This surface was set as “outlet” as the condition cannot be specified, which includes temperature, humidity and velocity.

5.4 Results

5.4.1 Experimental Results

Measurement data are collected and graphs are plotted for further analysis. The graphical results for trial 1 are shown from Figure 54 to Figure 56, whereas the graphical results for trial 2 are as shown from Figure 57 to Figure 59.

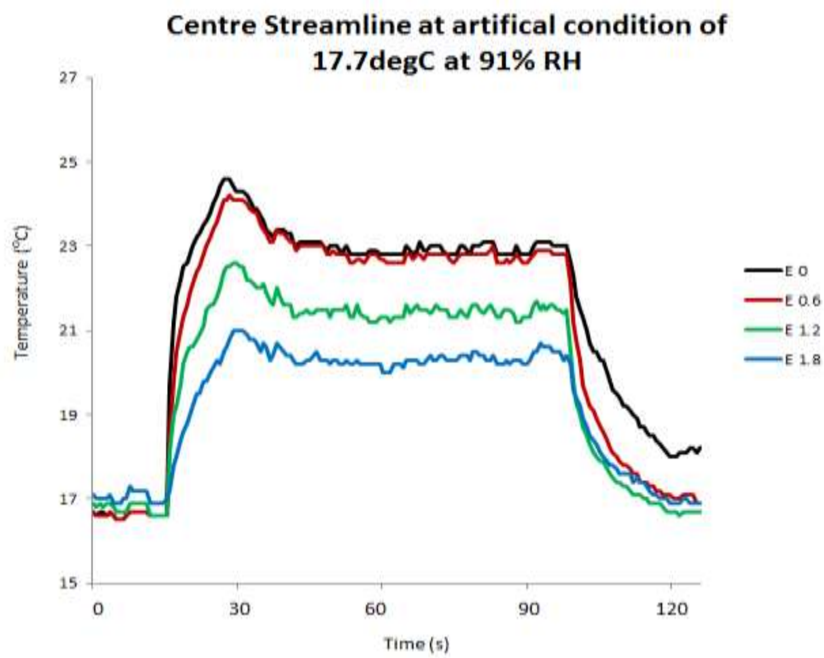


Figure 54 Temperature record of experiment with Formation A (Refer to Figure 45 and Figure 46) of Trial 1

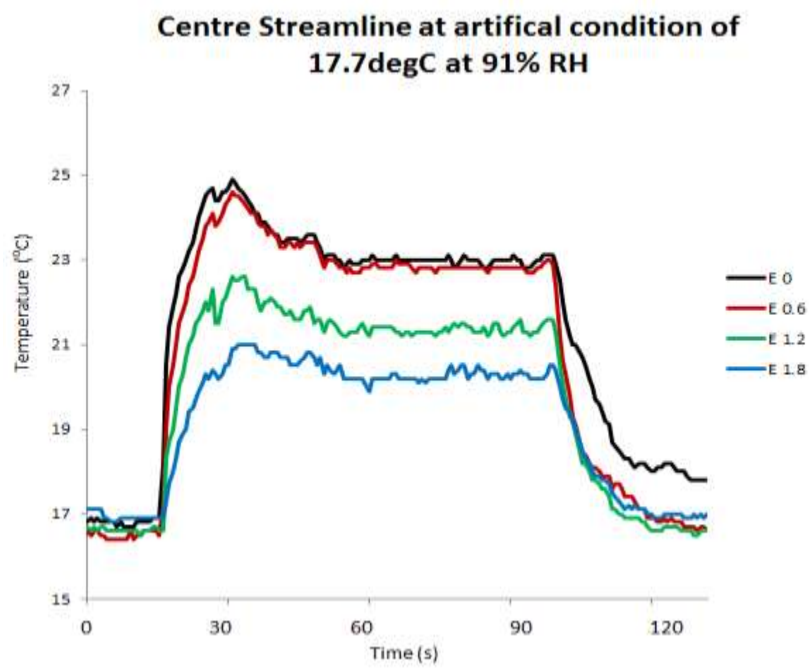


Figure 55 Temperature record of experiment with Formation B (Refer to Figure 45 and Figure 46) of Trial 1

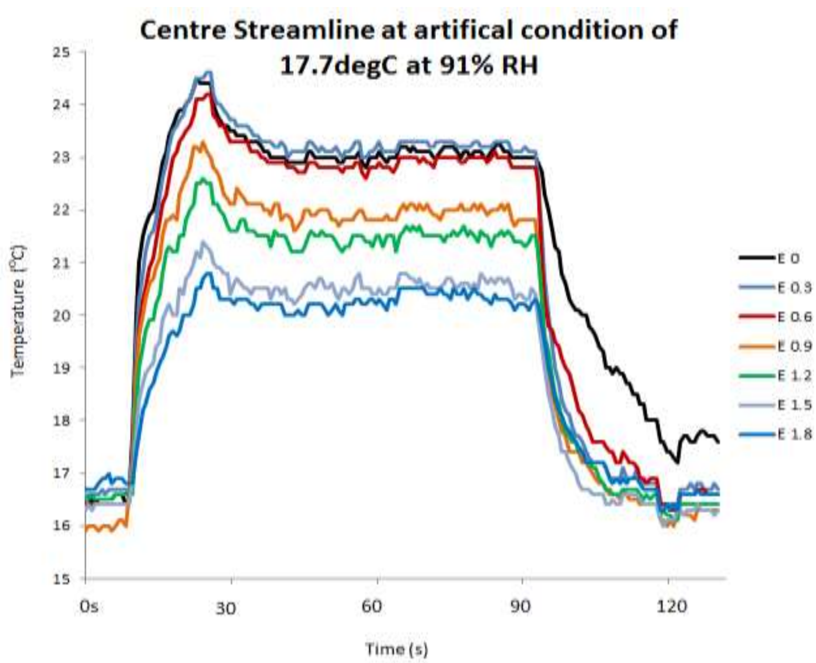


Figure 56 Temperature record of experiment with Formation C (Refer to Figure 45 and Figure 46) of Trial 1

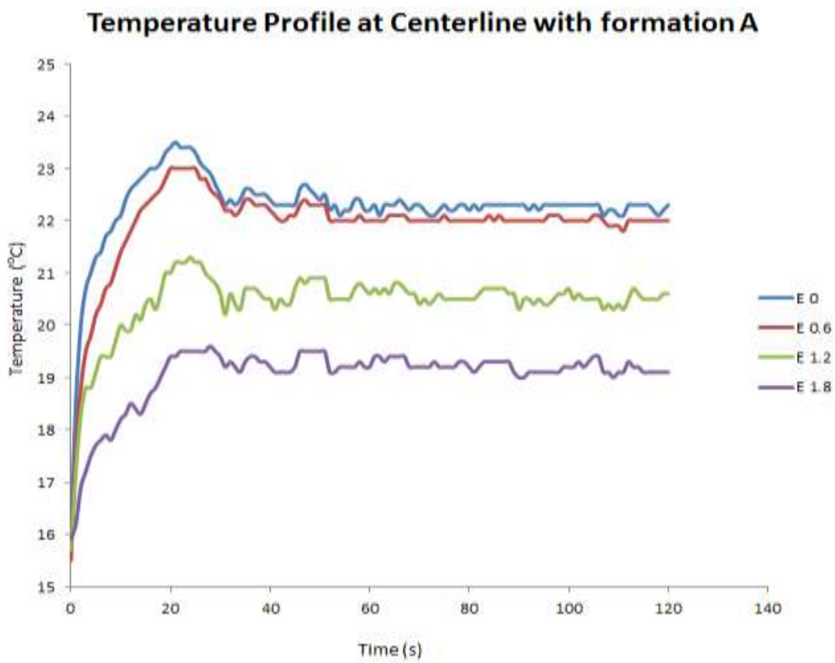


Figure 57 Temperature record of experiment with Formation A (Refer to Figure 45 and Figure 46) of Trial 2

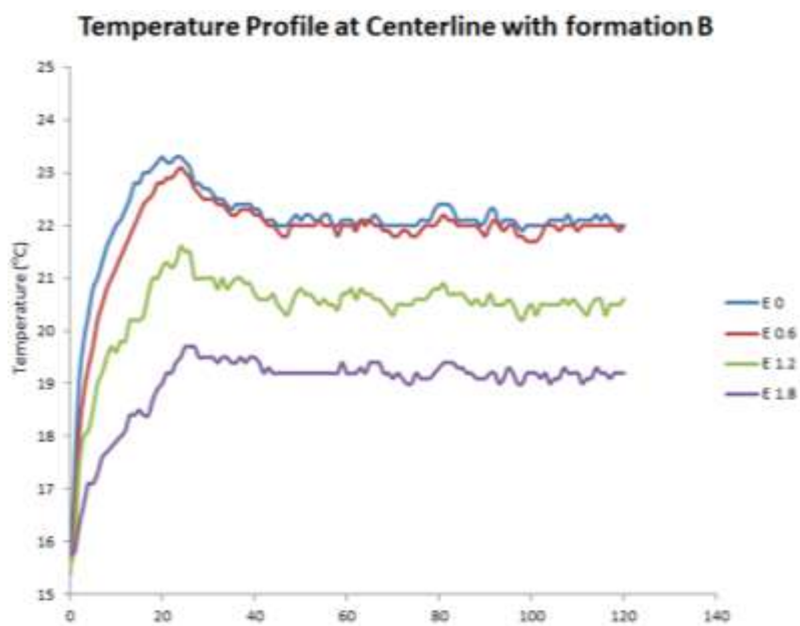


Figure 58 Temperature record of experiment with Formation B (Refer to Figure 45 and Figure 46) of Trial 2

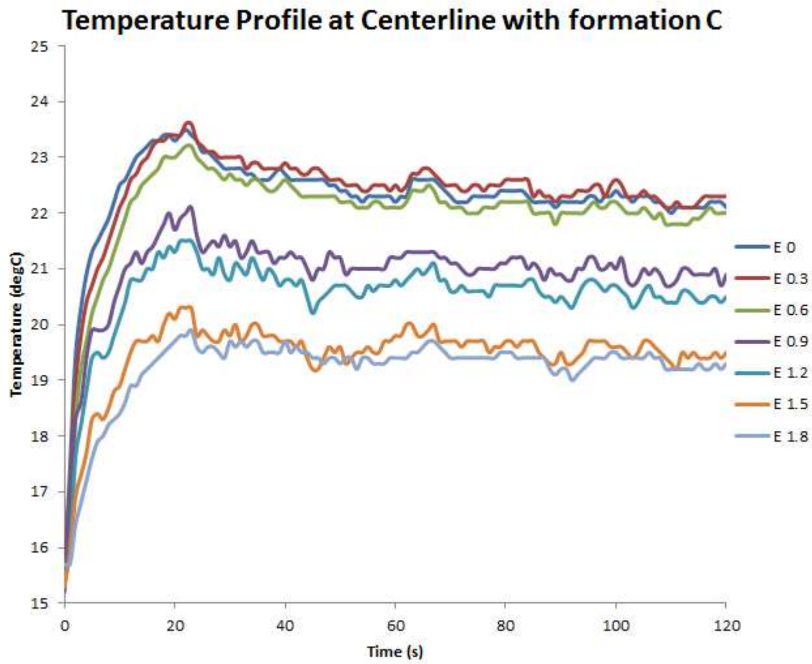


Figure 59 Temperature record of experiment with Formation C (Refer to Figure 45 and Figure 46) of Trial C

From the measurement results, it can be seen that the temperature rises immediately within seconds as the saturated and hotter air is discharged into the artificial environment. The temperature reaches the highest point between 25 – 30 seconds straight after the experiment begins.

However, temperature begins to drop since then, and eventually becomes steady at approximately 40 seconds after the experiment commenced. There is little fluctuation in temperature and within an acceptable range of ±0.5°C.

It must be noted that with formation A, B and C, the temperature profile and the fluctuation in temperature for both trials are very similar. Therefore, it can be concluded that the testing chamber is operating at a similar condition for the same trial; hence, data recorded for different formations but of the same trial (experiment for the same artificial environment condition and discharge condition) can be viewed as a single experiment and these results are used to compare with the results of CFD simulations.

5.4.2 CFD Results

In this study, two simulations were carried out with identical boundary condition as the experiment. The figures below showed the dispersion of plume with reference to the change in temperature as air was discharged upwards (where temperature is lower at the outlier point of the jet along the centreline and higher at the centre). By observation, the temperature profile was identical with the experimental results as shown in Figure 54 and Figure 59. However, further analysis was carried out to further justify the accuracy of the simulation.

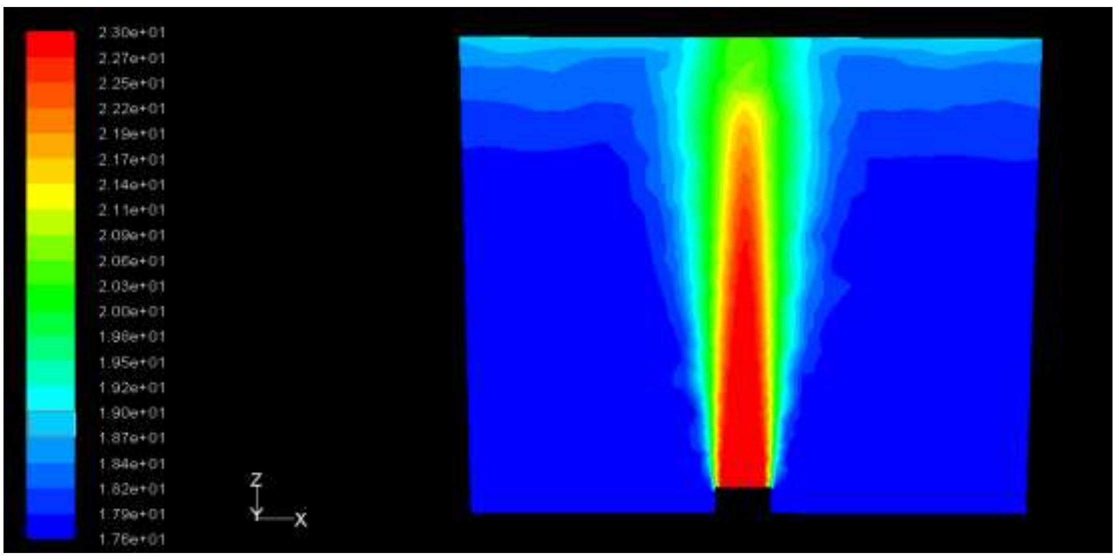


Figure 60 Results of CFD Simulation on temperature profile within the testing chamber of Trial 1

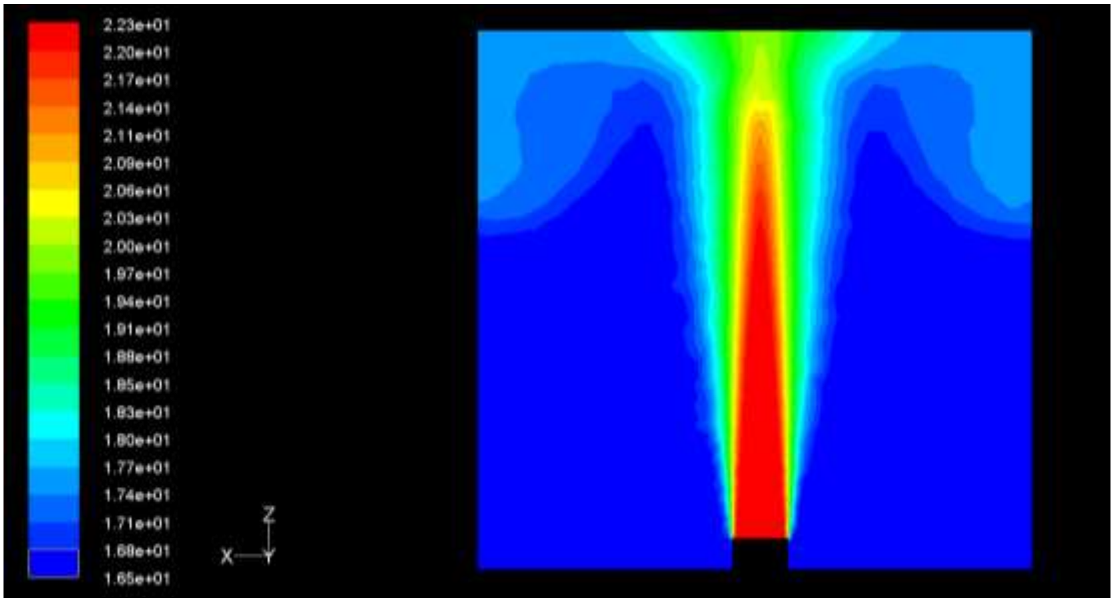


Figure 61 Result of CFD Simulation on temperature profile within the testing chamber of Trial 2

5.4.3 Experimental & Simulation Comparison

Results from CFD simulation were extracted for both trial 1 and trial 2 and data of the 3D simulation were extracted at the same location as the measurement in the artificial environmental chamber.

Figure 62 – Figure 64 show the comparison between CFD simulation and the experiment for trial 1, while Figure 65 – Figure 67 show the comparison between CFD simulation and the experiment for trial 2.

There were discrepancies between the CFD simulation results and the experimental measurement results at the higher position above the discharge jet because there were noticeable dews at the tip of thermocouples. Due to this reason, the measurement results tend to be at a lower temperature compared to the simulated results as no dew would be formed in the latter case. The dews were formed due to the high humidity level of the artificial environment, and also the air discharged into the chamber would not be able to blow the dews away from the thermocouples at a higher level above the jet.

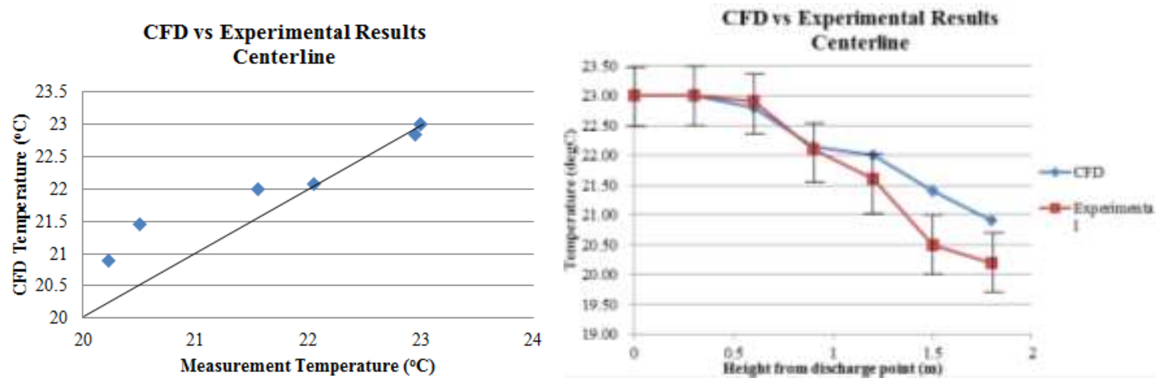


Figure 62 Experimental & simulation results comparison along centreline at various heights above discharge point for Trial 1

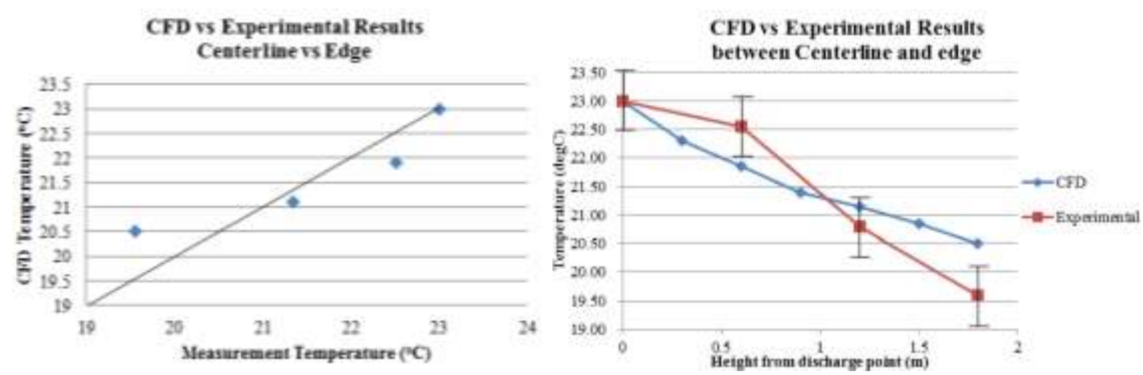


Figure 63 Experimental & simulation results comparison at mid-point at various heights above discharge point for Trial 1

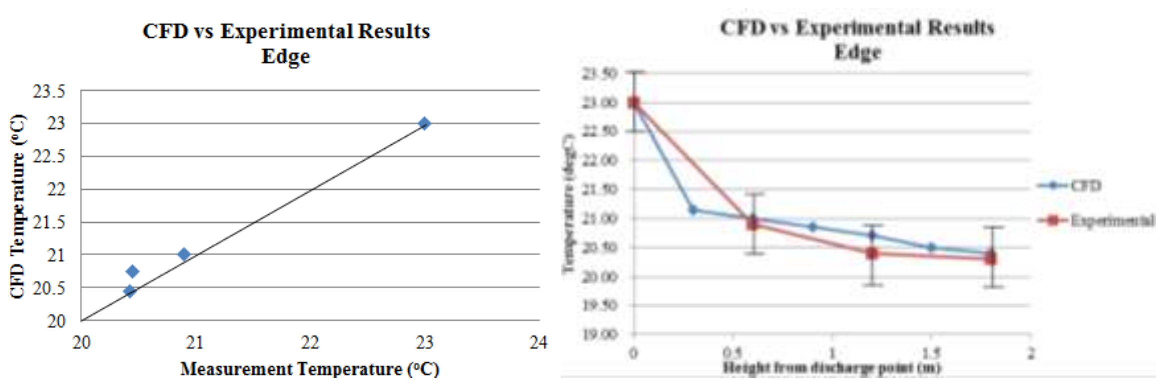


Figure 64 Experimental & simulation results comparison at the edge at various heights above discharge point for Trial 1

As can be seen from the comparison between the results of the CFD simulation and the experiment of trial 1, the general trends of the curves at all points of measurement are very similar with a variance of 1.0°C.

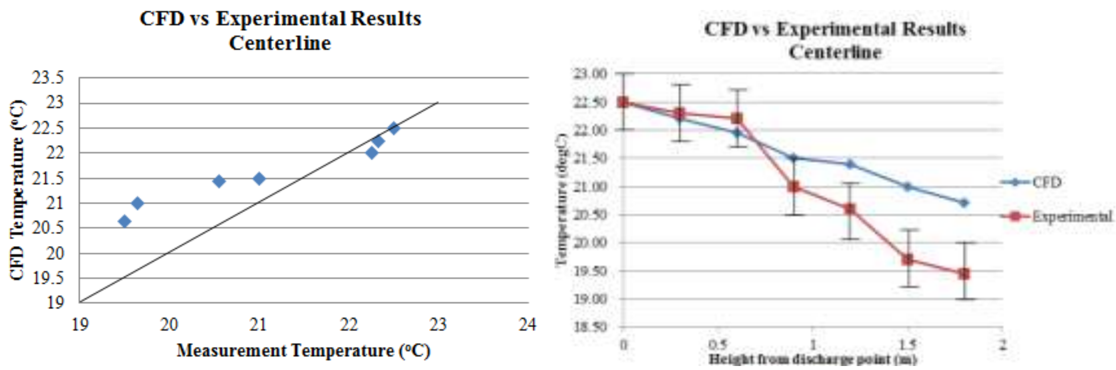


Figure 65 Experimental & simulation results comparison along centreline at various heights above discharge point for Trial 2

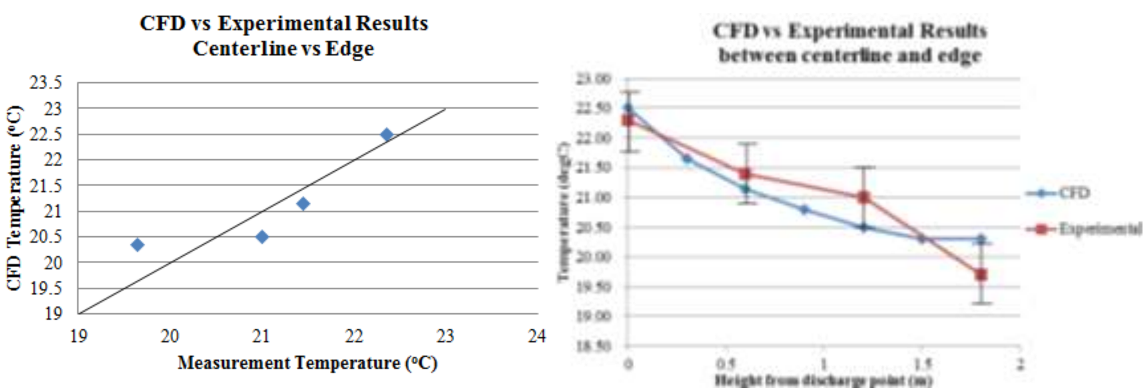


Figure 66 Experimental & simulation results comparison at mid points at various heights above discharge point for Trial 2

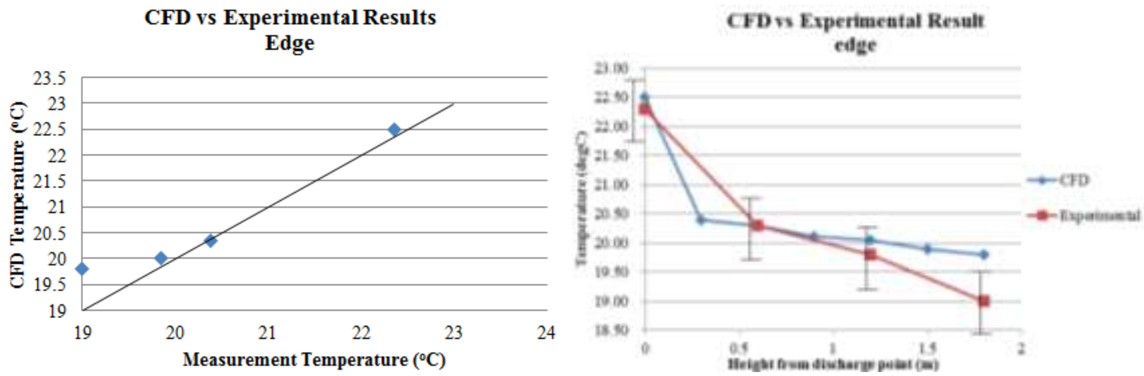


Figure 67 Experimental & simulation results comparison at the edge at various heights above discharge point for Trial 2

As for trial 2, the trends of the curves are also very similar between CFD simulations and the experimental results. However, the absolute values are fairly different between the CFD simulation and the experimental results, which the biggest difference is approximately 1.2°C.

Error bans have been incorporated to show that most of the CFD simulation results are within acceptable range with the experimental data. However, it should be noted that during the experiment, moisture condenses onto the surface of the sensitive areas of the thermocouples and thus may cause the temperature reading to be slightly less than expected.

When reviewing the simulation with respect to RH, it is found that the RH reading from the RH sensor is 100% (saturation) while the RH results from CFD simulation is 98% (see Figure 68). The results between experiment and simulation are close and show that the mathematical model is accurate for further simulation in Section 7.2.

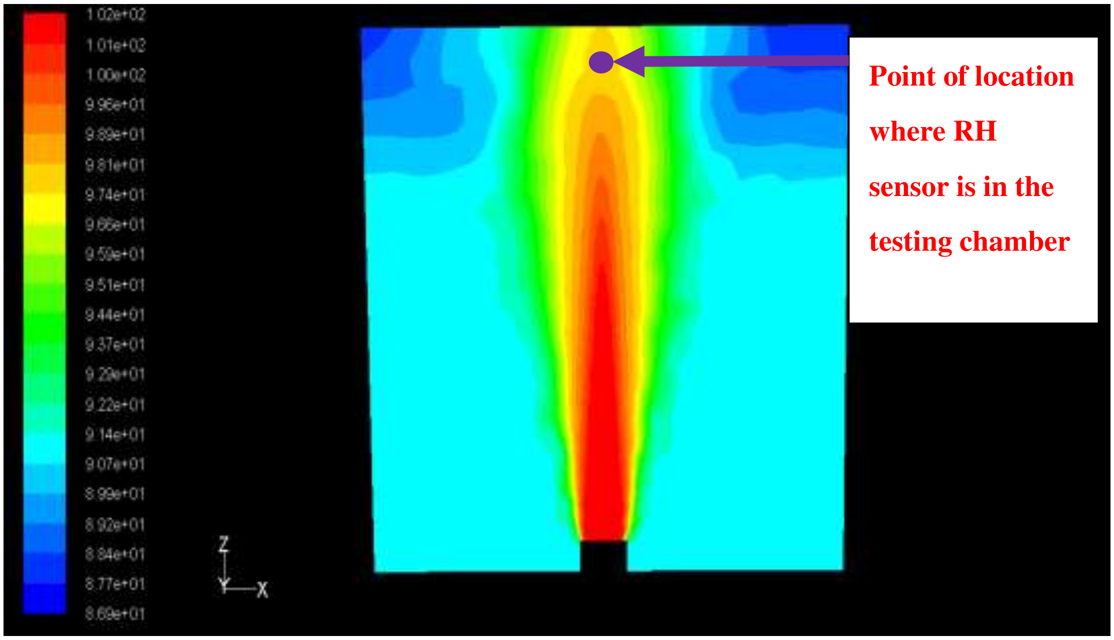


Figure 68 Simulation result of RH profile in the testing chamber

5.5 Summary

Based on this analysis, it can be seen that the temperature and RH between CFD simulations and measurement results are close with each other. This shows that the CFD simulation with the use of k-ε turbulence mode is acceptable for plume pattern. This suggests that this model is suitable to simulate cooling tower discharging saturated air into a humid environment.

Chapter 6 – Visible Plume Abatement for Cooling Towers

6.1 Introduction to Visible Plume

Commercial buildings in Hong Kong consume a significant amount of energy. Therefore, an energy efficient heat rejection system is a necessity to reduce energy consumption. Research has shown that electricity consumption for water-cooled system is more efficient than air-cooled system (Chen et al, 2008). Therefore, after the publication of the Code of Practice for Water-cooled Air Conditioning Systems by EMSD (EMSD, 2004), cooling towers are often adopted in new building design and existing system (system retrofitting).

Although cooling tower is more effective in heat rejection than air-cooled chiller, the discharged air in a form of visible plume from cooling tower has several adverse impacts to neighboring locations. This includes the spread of Legionella via airborne droplets (Hyland et al, 2007, Brown et al, 1999, Berk et al, 2006), equipment corrosion caused by condensation, misconception as smoke and air pollution due to view obstruction (EMSD, 2004).

Plume visibility is a result of water vapor condensation that occurs at regions where hot and moist discharge air is mixed with the cooler and humid ambient air. Plume visibility is largely determined by the climate, which a high potential for visible plume occurs when ambient air RH reaches 90% (Xu et al, 2008). The severity of visible plume is determined by the amount of moisture in the air, which the higher the RH of the environment, the more severe the visible plume.

Climate of Hong Kong is very humid because the city is geographically located next to the Southern China Sea. Based on the Hong Kong climatic data of 2009, there were a total of 1,288 hours with ambient RH over 90%, of which 501 hours and 320 hours were recorded in spring and winter respectively. It is also during these seasons that cooling tower visible plume was most severe because of the low moisture holding capacity at low ambient temperature.

Water shedding approach was proposed in this chapter to reduce visible plume severity and frequency of it while to ensure the cooling towers were operating at condition as design intent.

Analysis was carried out in a cross-flow cooling tower plant of a typical office building in Hong Kong.

6.2 Modeling of Potential of Plume

Psychrometric chart is adopted in this study as it provides quick recognition on both plume visibility and severity. Figure 69 shows a psychrometric chart with the saturation curve to illustrates the capacity of dry air to hold moisture at different dry bulb temperature. In theory, the water holding capacity decreases as the dry bulb temperature decreases.

The psychrometric chart of Figure 69 demonstrates two simple scenarios; one is a cooling tower operating in a wet and humid environment (Line 2-1) and another one operating in a relatively hotter and drier environment (Line 4-3).

As cold and humid ambient air at condition 1 is heated up to condition 2 in the cooling tower, the discharged air remixes with the ambient air and temperature decreases along the line 2-1. As the temperature drops, moisture content drops simultaneously. However, at a certain range of temperature along line 2-1, the moisture content in the air exceeds the moisture storage capacity of dry air. This results in condensation, which the total potential of condensation is as illustrates within the green area as shown in Figure 69. In contrast, when a cooling tower is operating at a relatively hotter and drier atmosphere, potential for visible plume to appear reduces significantly as the mixing line does not intersect the saturation curve.

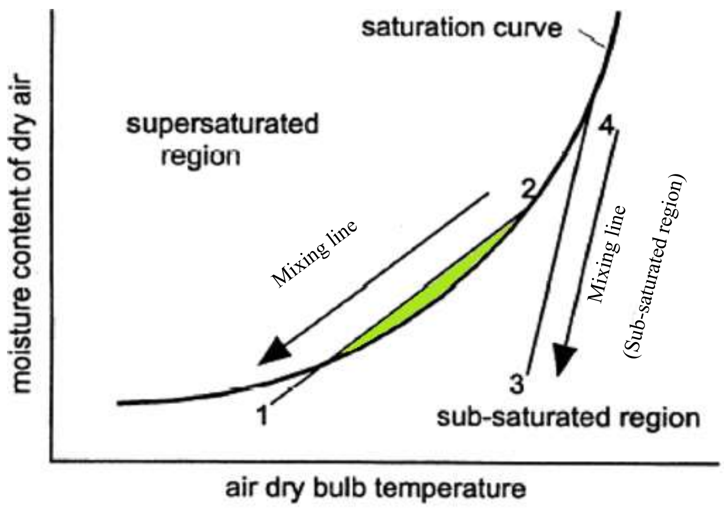


Figure 69 Psychrometric chart for visible plume analysis

The green area represented by line 2-1 in Figure 69 is identified as the potential of condensation, which Tyagi, Wang and Ma (Tyagi, et al, 2009) suggested that the greater the green area there would be a higher potential of condensation and leading to visible plume.

The area of intersection can be evaluated using some standard mathematical formulation with definite integral as shown in equation (33)

$$A = \int_{w_2}^{w_1} [f(sat\ line) - f(air\ mixing\ line)]dw \qquad (33)$$

where w_1 = Air inlet humidity ratio (g of water vapour per kg of dry air)
w_2 = Air discharge humidity ratio (g of water vapour per kg of dry air)

Potential of Plume (POP) index is proposed to compare the 'severity' of plume, which incorporates with Tyagi, Wang and Ma (Tyagi et al, 2007) model.

$$Relative\ POP\ Index = \frac{A_d}{A_{ew}} \quad (34)$$

where A_d = Area of the intersection to the left of the saturation curve in the Psychrometric chart under discharge condition

A_{ew} = Area of the intersection to the left of the saturation curve in the Psychrometric chart under extreme weather condition which the RH of the outdoor air is 90% or above.

6.3 Visible Plume Abatement

6.3.1 Heat Coil Approach

In the industry, the commonly adopted approach for visible plume abatement was to install heating coils in a cooling tower as shown in Figure 70 to reduce the severity of visible plume. Air would be drawn into two sections, with one section drawing air into the film to carry out the heat exchange process between water and air, while the other section where air would be drawn into the heating coils to heat the ambient air . The two streams of air of different conditions would then be mixed within the tower and causes the RH of air be reduced, thus reducing plume visibility.

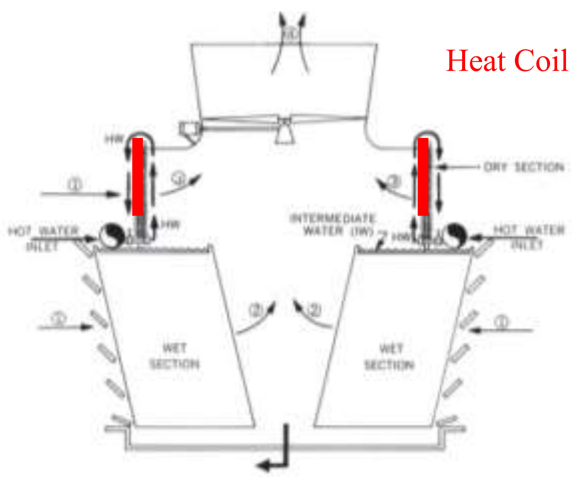


Figure 70 Configuration of a heat coil visible plume abatement cooling tower [Hensley, 2009]

However, there are disadvantages with this approach, which are source for heating, unreliability for visible plume abatement and the installation of heating coils reducing the tower performance.

Source of Heating

Heat coil can be heated by heat pumps or by electricity source. With the former, it is not common in Hong Kong as the tropical climatic condition do not encourage buildings to use heat pump. The latter is more common, but additional system will be required to provide electricity for heating purpose.

Unreliability

Heating of the coils usually requires a significant amount of time, especially with heat coils that needs to heat air at a temperature 10 – 15^{o}C higher than ambient air. From practical view, sometimes it takes possibly five to ten minutes from starting till when the coils are at maximum performance.

Reduce of cooling tower performance

By installing a cooling tower with heating coil as shown in Figure 70, the height of the tower will be increased, thus increasing the static pressure of the tower, and requires higher power consumption.

There are also other cooling tower designs that adopts heat coil, which heat coils are installed at either the points where air enter or exit the fill as shown in Figure 74. However, this approach will also cause cooling tower performance to be reduced, where the close proximity of coil near the fill will cause the coils subject to water impingement and resulting with scaling and restriction to flow.

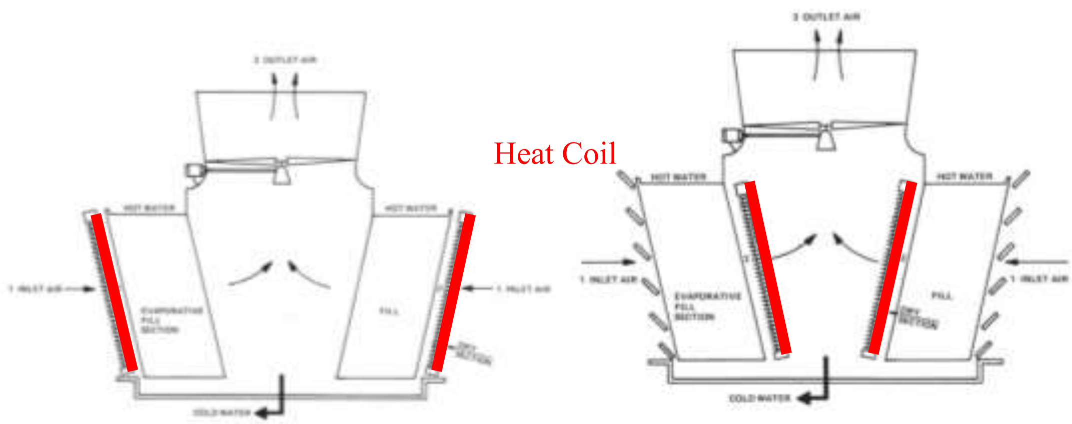


Figure 71 Heat coil installed at entrance point of fill (Left) and at exit point of fill (right) [Hensley, 2009]

If cooling tower requires constant visible plume abatement throughout the year, it is acceptable to adopt the heat coil approach; however, as visible plume does not happen all the time, a lot of energy will be wasted at times when plume abatement is not required.

6.3.2 Water Shedding Approach

Due to the disadvantages of the heat coil approach, the water shedding approach is proposed that does not share the same disadvantages. The first step of the water shedding approach is to undertake an analysis on visible plume abatement, it is important to define the frequency of visible plume appearance, which is determined by the climatic condition in Hong Kong.

In the analysis, the climatic data of 2009 from the Hong Kong Observatory is used. In contrast, the severity of visible plume is determined by the cooling tower plant design and the cooling load requirement. The frequency and the severity of visible plume are considered in the visible abatement program, which the logic flow is as shown in Figure 72.

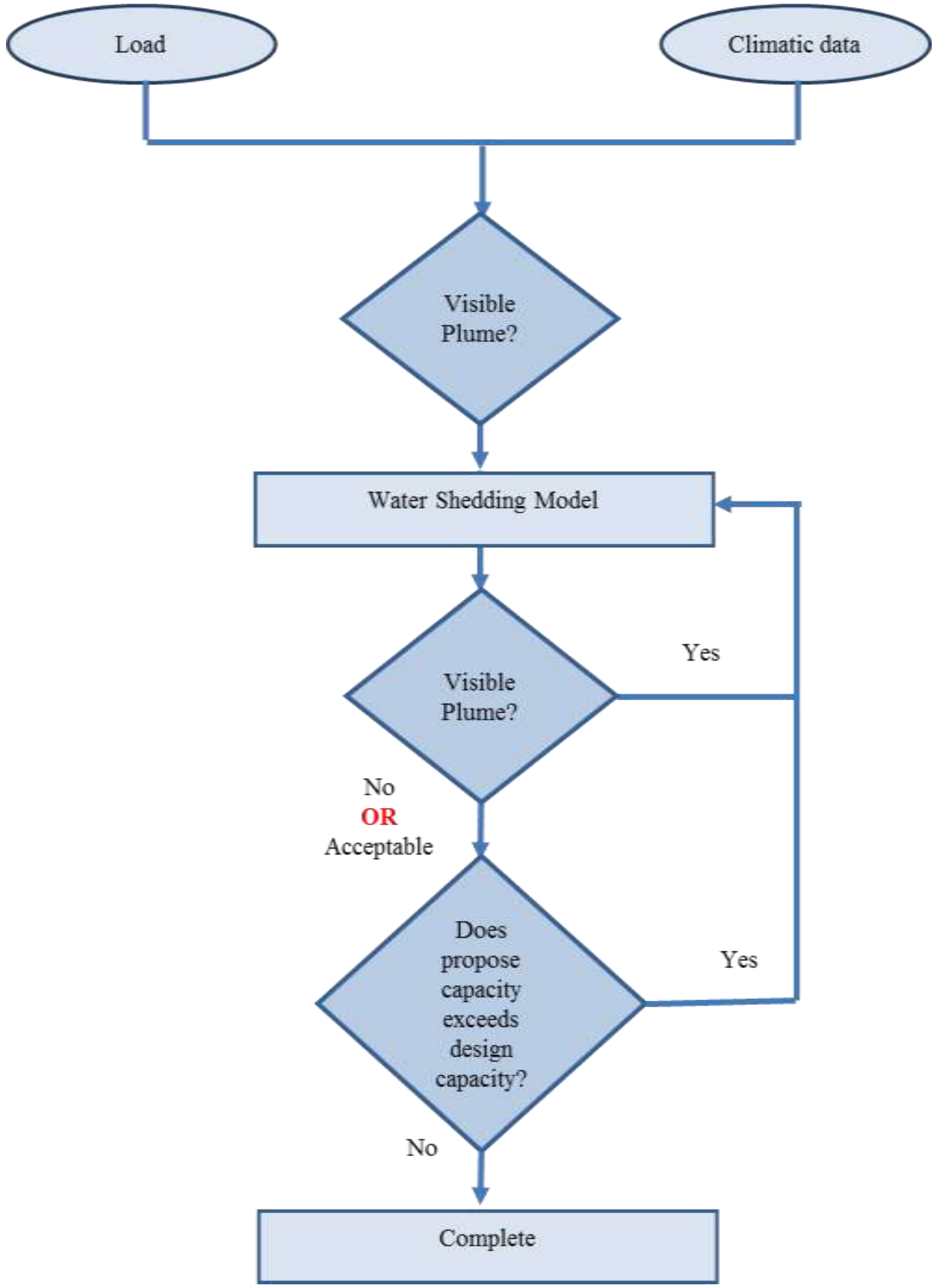


Figure 72 Logic flow of visible plume abatement

The water shedding approach is proposed with the adoption of Poppe Approach in a scenario where a plant has a total of five groups of cooling towers which each group contains three cooling towers and one smaller group that consists of two cooling towers per group (total of 17 cooling towers). During operation, the operating pressure at the water side must remain the same for all cooling towers to ensure no backflow of water.

The minimum flow rates for both water and air are taken into consideration in the water shedding approach. This is because the change in flow rate changes the heat rejection rate, discharge air and water conditions and most importantly, the number of cooling tower that needs to be in operation to deliver the same heat rejection rate while reducing visible plume severity. The logic flow of the water shedding approach is as shown in Figure 73.

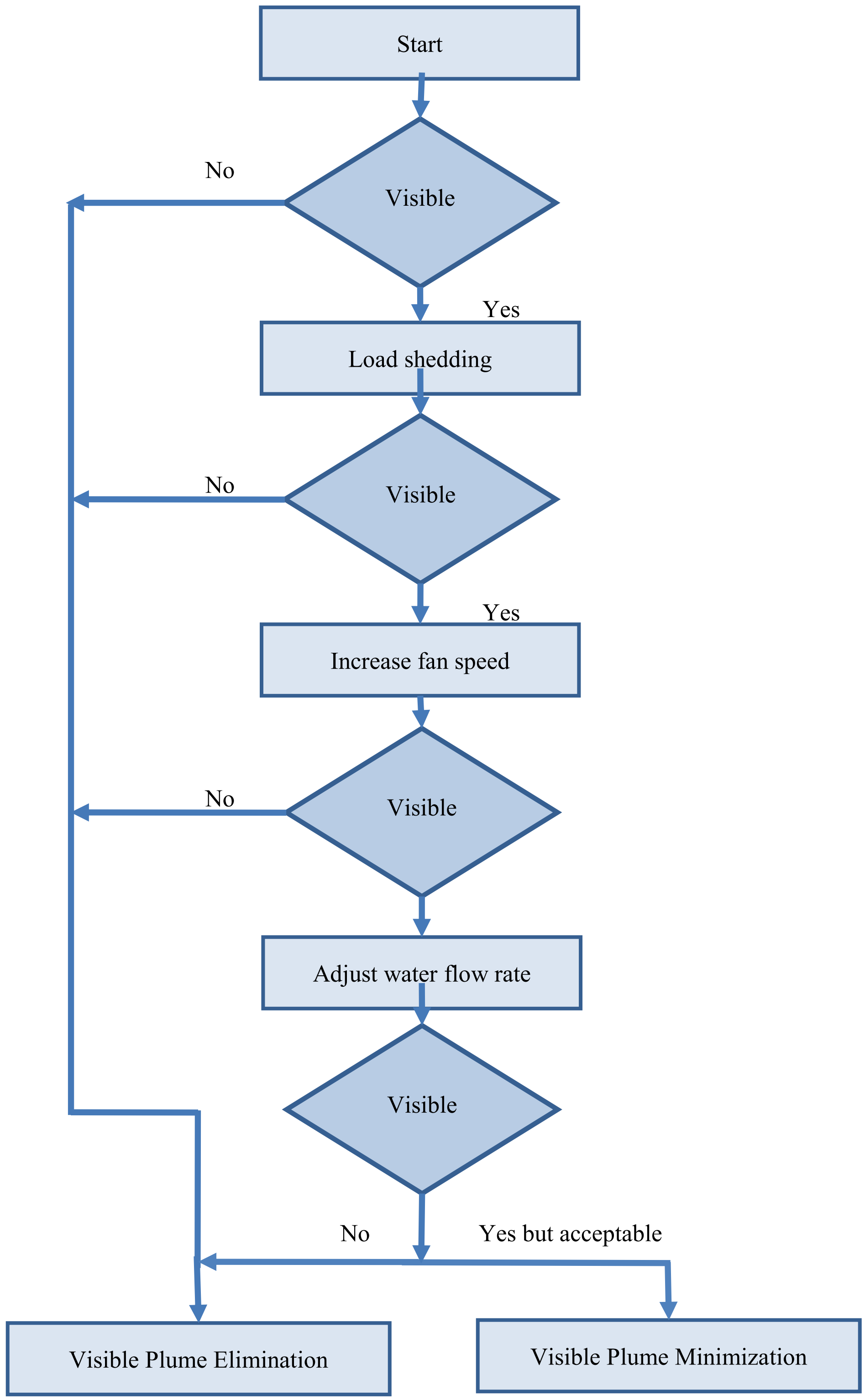


Figure 73 Logic flow of water shedding approach

6.4 Results and Discussions

6.4.1 Potential of Visible Plume with Maximum Load of Plant

In order to analyze the visible plume frequency and severity, the required information would be the climatic data of Hong Kong. By using the climatic data, the cooling load of the New Civil Aviation Department Headquarter is used that is calculated with Equest, and based on the building load to calculate the energy consumption of the cooling tower plant. The building consists of three wings which the first wing consists of the new energy centre for the complex, the second wing consists of the Air Traffic Control Centre, offices, training facilities, conference facilities and auditorium the third wing is for aviation antennae facilities. The building is a low rise building with a gross floor area of 41,000m^2. The developed water shedding approach is used in this building in order to show the frequency and severity of visible plume can be reduced. Note however that the water shedding approach can be used in any types of building as long as there is cooling tower installed.

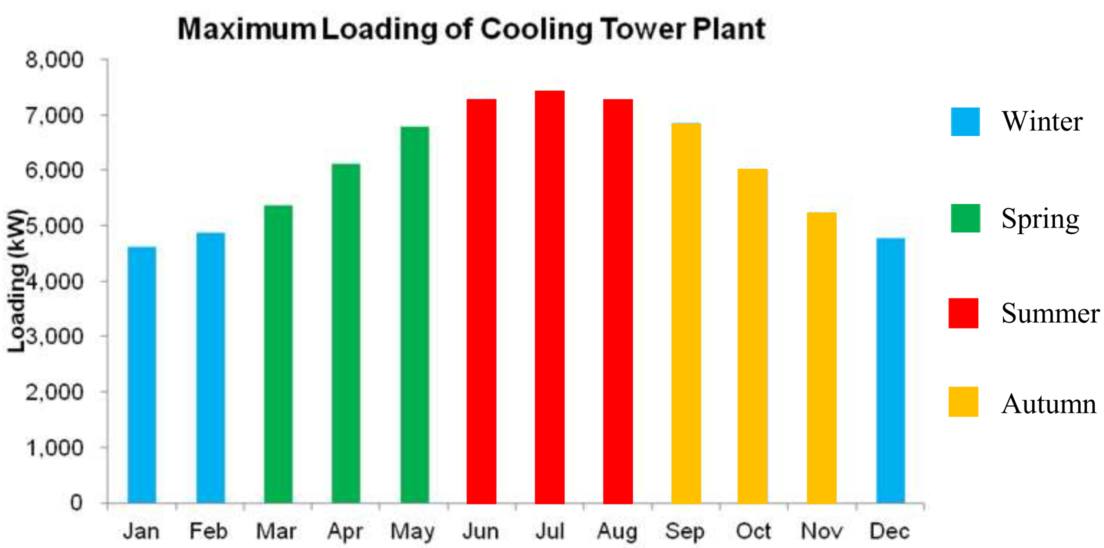


Figure 74 Maximum loading of the cooling tower plant

In summer, much energy is required to cool the indoor environment, thus much heat is needed to be rejected via the cooling tower plant. In contrast, less energy is required in cooling during winter, thus the plant loading is proportionally smaller. These data are shown in Figure 74.

As aforementioned, there are a total of 1,288 hours that RH is equal or higher than 90%. This suggests that 15% of the time in 2009 has a high tendency of visible plume occurrence, and the amount of time is used as a reference for the determination of POP.

6.4.2 Shedding Approach and POP

Within the 1,288 hours, 320 and 501 hours are during winter and spring respectively. During these relatively cooler and moister seasons, cooling tower plant do not at full capacity, which the plant loading in winter (blue bar) and spring (green bar) as shown in Figure 74 are ranging between 64 ~ 66% and 73 ~ 92% of maximum plant loading respectively. This provides opportunity to carry out visible plume abatement with the water shedding approach.

Analysis shows that the visible plume frequency of the designated plant is 1,047 hours, which is 12% of the time within a year. The distribution of visible plume frequency is as shown in Figure 75, which March has the highest frequency of occurrence with a total of 214 hours.

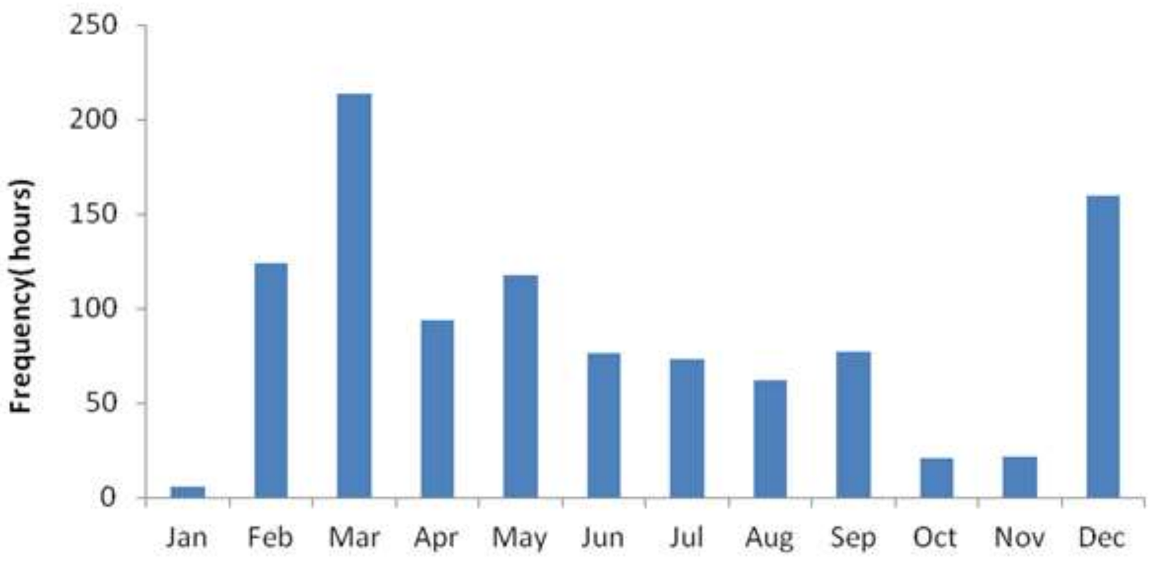


Figure 75 Frequency of visible plume in 2009

In the analysis for visible plume severity, high atmospheric RH condition of 90% and above is used as a reference to calculate the POP index. Figure 76 shows the POP index of the year 2009, which higher the value represents a more severe visible plume.

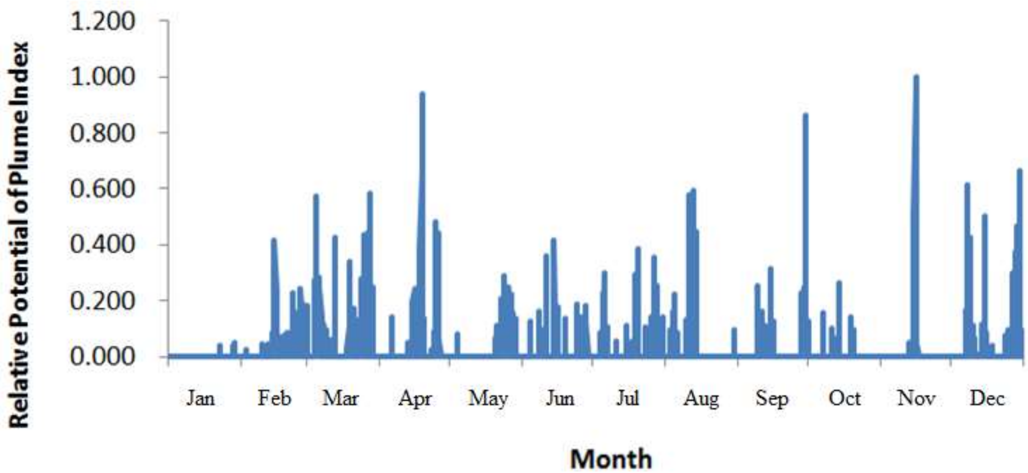


Figure 76 POP Index on visible plume severity in 2009

By adopting the water shedding approach, the frequency of visible plume reduces from 1,047 hours to 647 hours. A comparison between the use of water shedding approach and without the use of water shedding approach with respect to visible plume frequency is as shown in Figure 77.

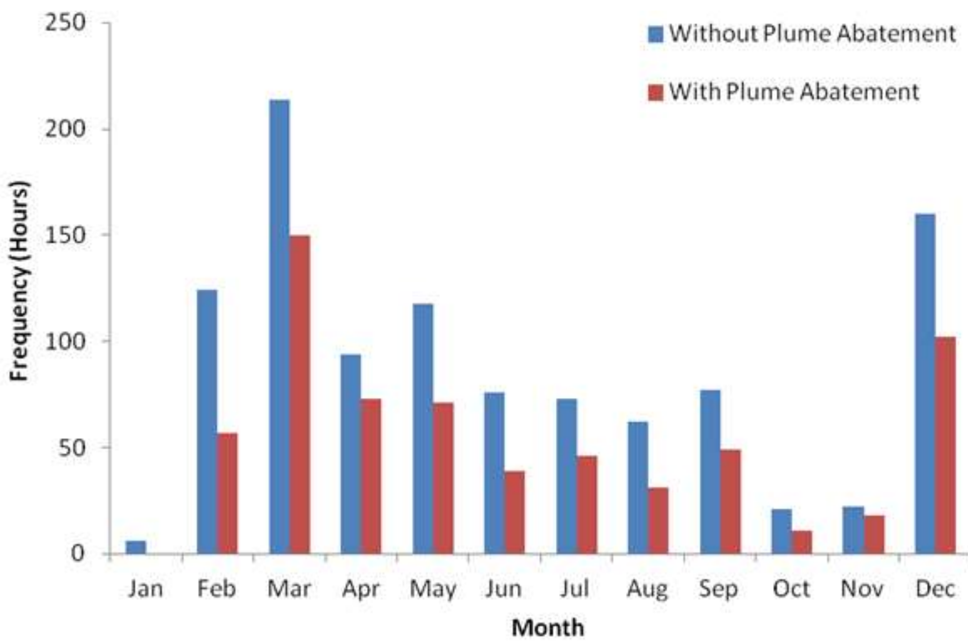


Figure 77 Comparison of visible plume frequency

Although at certain period of time that cooling tower plume still remain visible, but the severity is reduced significantly. Figure 78 shows the severity of visible plume within the 647 hours of occurrence is reduced by 40 ~ 60%.

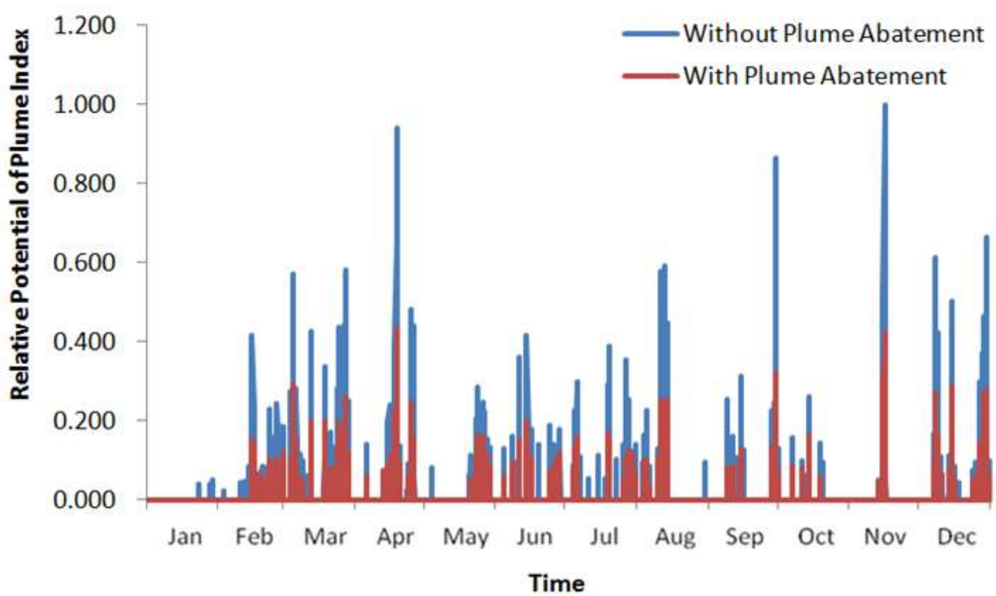


Figure 78 Comparison of POP Index on visible plume severity

6.5 Summary

Water cooled chiller with cooling tower is 20 ~ 30% more efficient than air-cooled chiller, thus many developments adopts water-cooled system instead of air-cooled system in new construction or existing plant retrofitting. However, visible plume is a nuisance in an urban city in respect to human and equipment healthiness. Therefore, a dynamic and accurate simulation program is required to predict and evaluate visible plume frequency and severity.

The water shedding approach is proposed for visible plume abatement. The POP index is proposed to compare the 'severity' of plume between the use and without the use of water shedding approach.

By adopting the Hong Kong 2009 climatic data, the evaluated cooling tower plant has a visible plume frequency of 1,047 hours, in which 214 hours occur in March when the cooling tower plant is operating at 73% of full capacity.

In the evaluation, the water shedding approach reduces the visible plume frequency into 647 hours, which is 62% of the original case without use of water shedding approach. Furthermore, the severity of visible plume can be reduced by 40 ~ 60%.

It is worthwhile to use the water shedding approach, as it proves to be effective in reducing frequency and severity of visible plume. Furthermore, cooling tower plant adopting the water shedding approach is more effective than the use of cooling tower with air heating application as no modification is required in plant design and has lower operation energy consumption.

Chapter 7 – CFD Analysis of the Cooling Tower Plume

7.1 Introduction

Within an urban city, cooling tower discharge is not merely a visual concern but also a health impact to citizen. In Hong Kong, some small towers are located at ground level and very close to the pedestrian level.

An investigation of plume formation mechanism and appearance is conducted in this study, so as to determine the effect of moist plume in urban area. The primary objective is to capture the plume transport behaviors around a cooling tower being operated within a narrow alley. In this chapter, CFD simulation is used to carry out a case study to identify the flow of visible plume under different wind condition and different location of cooling tower within an urban environment. However, instead of carrying out a simulation in a specific location, a general model is created to simulate an environment that is similar to an actual urban environment.

7.1.1 Problematic Issue of Plume in an Urban City – Hong Kong

In Hong Kong, because of the compact built environment, small-scale cooling towers are commonly found in-between alleys of residential buildings. As aforementioned, cooling tower has a potential in spreading Legionella if place close to people and should be placed at location as afar from populated area as possible. This misplacement of cooling tower is becoming more hectic if cooling towers are not operated in according to the guidelines of COP.

In order to identify the flow pattern of visible plume, location of the cooling tower must be identified first to ensure the simulation is similar to real case. According to the COP of cooling tower of Hong Kong, the location is to maintain a minimum of 7.5m away from the opening in horizontal, which are as shown in Figure 79 and Figure 80.

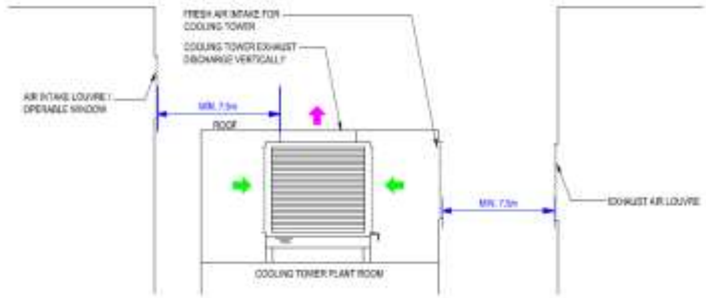


Figure 79 Section view of cooling tower and minimum distance away from air intake/exhaust point

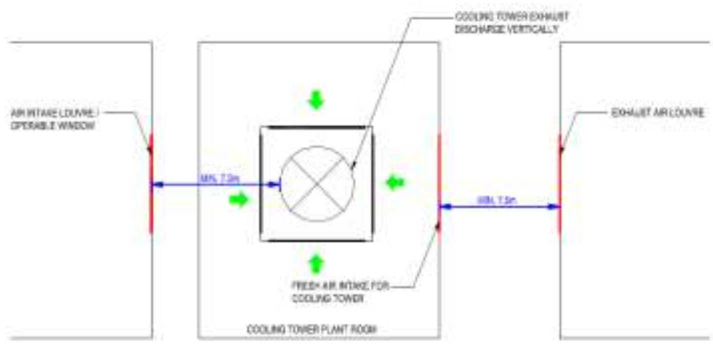


Figure 80 Plan view of cooling tower and minimum distance away from air intake/exhaust point

The objective of setting up the constraints on cooling tower location is to eliminate cooling tower discharge to have any health impact. However, there are still cases where cooling towers are not located at acceptable location. Figure 81 shows a cooling tower located within an alley between two buildings and can be access by pedestrian very easily. If cooling tower is not maintained properly, there is high potential that the discharge contains contamination and spread disease, such as Legionnaires' Disease quite easily in this type of environment.

Figure 81 Cooling Tower located close to pedestrian levels

There is also evidence that adoption of cooling tower has a high tendency to spread Legionnaires' Disease with cooling tower since the year 2000 with more cooling tower installation. Department of Health (DoH) of Hong Kong has published the statistics of Legionnaires Disease (refer to Figure 10).

7.2 CFD Simulation Model Setting

7.2.1 3D Model

In the 3D model, the location of the cooling tower in this study is constructed on the ground level to simulate a condition similar to the case as shown in Figure 81 where cooling tower discharge is largely affecting pedestrians and adjacent buildings.

A 3D computation model was constructed for this study and similar to the one carried out by Liu and Chen (Liu & Chen, 2005) where one block was placed in front of a cooling tower and simulate the discharge flow pattern on CFD.

However, only with one block cannot provide a good indication of the flow pattern in an urban city. Scientifically, there are three types of flow characteristic in an urban city, which are isolated roughness flow, wake interference flow and skimming flow. The flow patterns are strongly correlated with the configuration of building height (H) and building width (W), which different types of flow pattern varies with variation in spacing between buildings as shown in Figure 82.

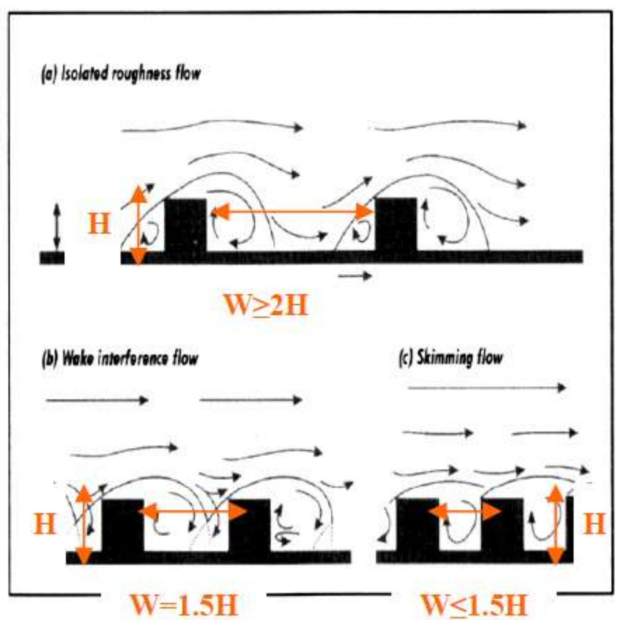


Figure 82 Flow patterns in an urban city with variation of H/W (PlanD, 2006)

Hong Kong is an urban city with many regular streets where the spacing between buildings can be very narrow (see Figure 83), and skimming flow is very usual with prevailing wind blowing perpendicular (+/- 30^{o}) to the streets and enters the street with the same flow pattern as shown in

Figure 82 – (c) skimming flow. This configuration with buildings at both sides of the street is referred as “wind canyon”.

Figure 83 City configuration of Hong Kong

Figure 84 shows a simple 3D computation model that is aimed to simulate a wind condition with turbulence effect similar to that of an urban city, and Hong Kong has the highest urban agglomeration of the world [CTBUH, 2009].

In the model, there are a total of 15 blocks, where the cooling tower is located between the 10^{th} and the 11^{th} block. The dimension of the computational domain is 1,760m (L) × 200m (W) × 1,350m (H) with 15 blocks of dimension 40m × 200m × 40m, for wind development, which the gap between the blocks is called the “wind canyon”. It must be noted that the height of the block is the same as the spacing between blocks in order to provide a stable vortex within the wind canyon, which the ventilation effectiveness is very low (Brown & Dekay, 2001), and is suitable to carry out plume dispersion analysis under this adverse condition.

The separation distance between the blocks is also 40m, which allows wind to be drawn into the wind canyon. Cooling tower is not placed at the first few wind canyons because the wind turbulence is not fully developed. When the wind turbulence is fully developed, the profile in each wind canyon will become relatively identical.

From the study, it is found that turbulence flow within each canyon is almost identical after the 6th or the 7th wind canyon in the simulation. However, to ensure that the cooling tower is located in a wind canyon with a fully developed turbulence flow, the cooling tower is located at the 10th wind canyon.

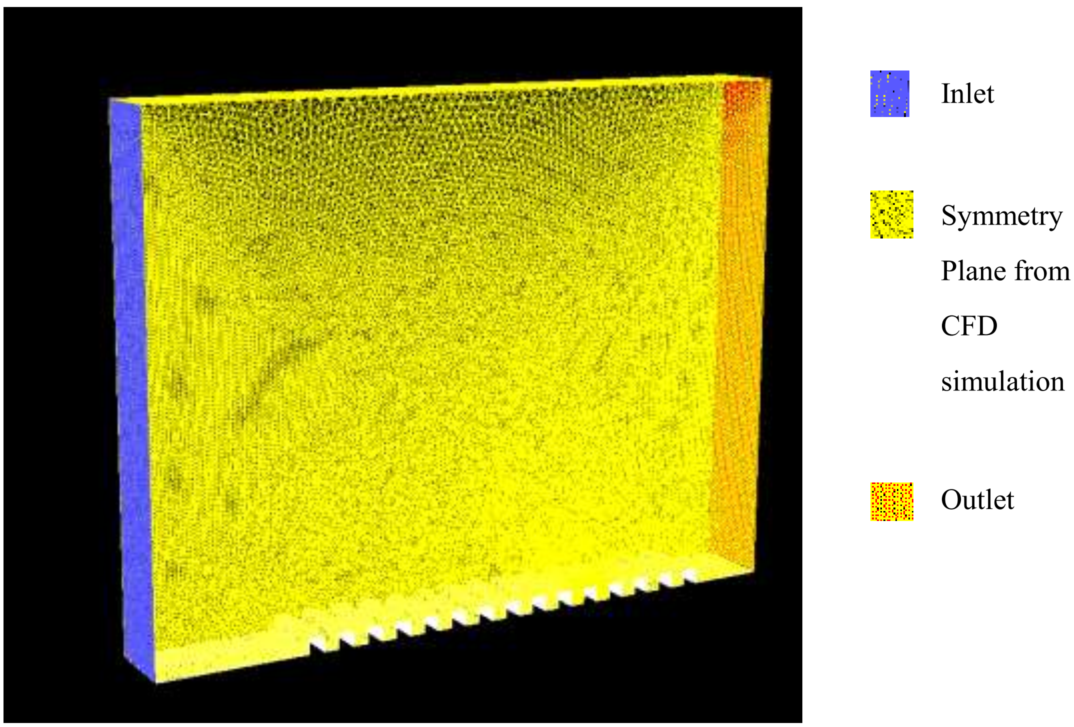


Figure 84 3D model of the domain for visible plume analysis

It is necessary to have a 3D model with a great height with reference to Tominaga, which the blockage ratio for CFD simulation can be made reference from the knowledge of wind tunnel testing and do not exceed 3% (Tominaga et al, 2008), In this model, the height of the domain is built as high as 1,350m in order to ensure the blockage ratio is maintained at 3%.

The dimension of the cooling tower in the 10th wind canyon (between the 10th and the 11th block) is 3m × 3m × 3m as shown in Figure 85, which the distance of 40m between the two blocks is labeled as D_{tot} and the distance from the wall of the windward side to the centre of the cooling is labeled as D_o. This will allow for calculation of the Distance Ratio (D_{ratio}) represented by Equation (35).

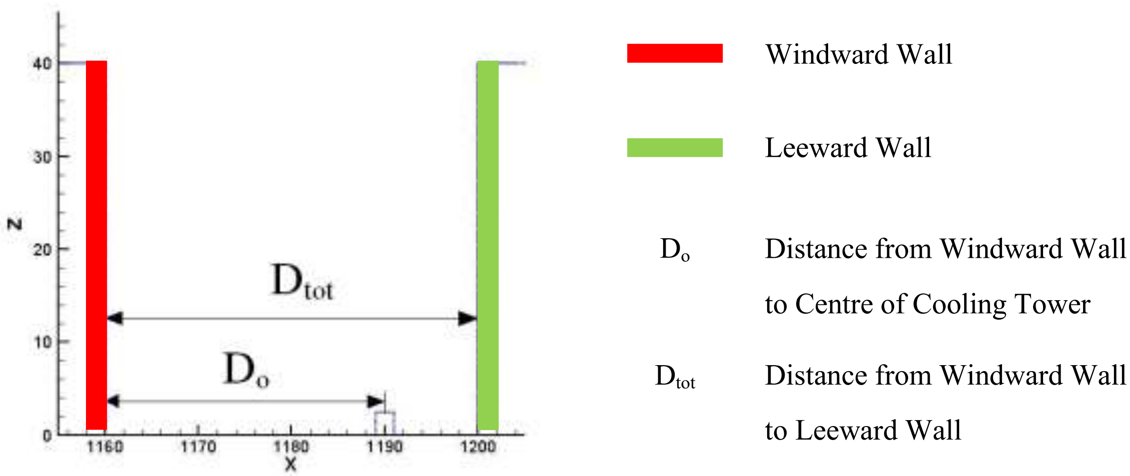


Figure 85 Computational Domain of cooling tower within an alley

$$D_{ratio} = D_o / D_{tot} \qquad (35)$$

In this analysis, cooling towers are placed at three different locations within the alley, which are distance closest to the windward wall, centre of the alley and distance closest to the leeward. Note that as the COP for cooling tower in Hong Kong is to ensure a minimum distance of 7m from intake louvers. Therefore, the distance of the cooling tower from either of the walls are maintained at a distance more than 7m to ensure that location of cooling tower is maintained at distance meeting the COP requirement.

As for the configuration of the cooling tower, ambient air will be drawn into the tower from both side of the tower and the relatively hotter and more humid air will be discharged from the top of tower.

7.2.2 Grid Size

The 3D model is constructed with the use of a program – Gambit, and tetrahedral mesh is used for meshing of the internal environment of the chamber. Tetrahedral mesh is used as it is easier to mesh with cylindrical object within the domain and it reflects better on the airflow pattern for CFD simulation. The 3D model is constructed with 1.6 million to 1.8 million tetrahedral meshes.

The grid size for the area of interest, the cooling tower and the surrounding area (area for air movement), has a finer grid size, which the size is suggested to be approximately 1/10 of the scale of the target object of interest [Yoshie et al, 2005]. With this respect, the grid size of 0.1m is set for the cooling tower.

In the simulation, the walls within the 10th wind canyon are identified as Windward Wall and Leeward Wall as specified in Figure 86, which is used to identify the highest moisture content on this wall and compare with the ambient moisture content under the two different discharge air conditions (with and without the water shedding approach).

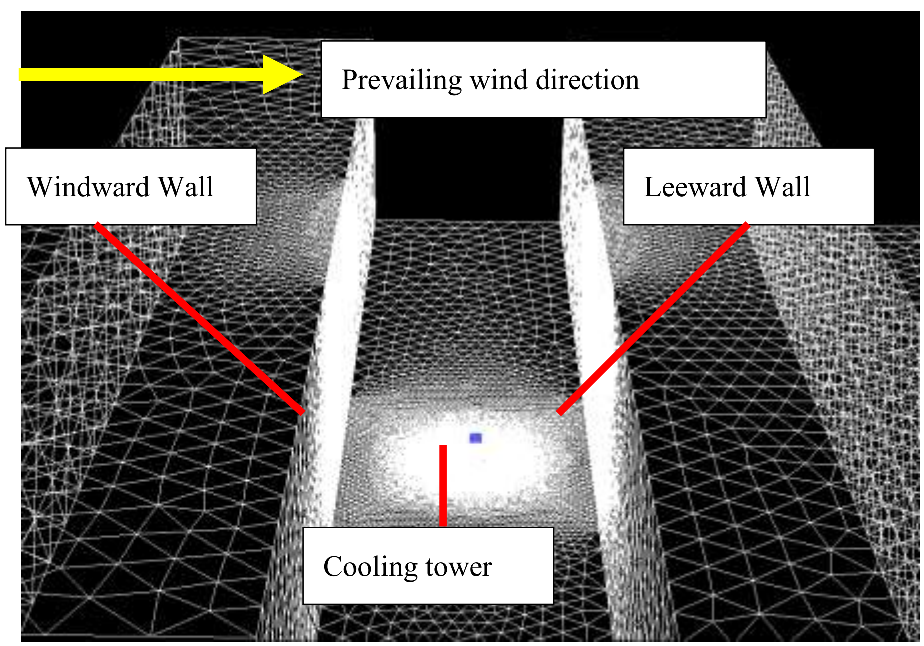


Figure 86 Configuration of the 3D model with cooling tower in the wind canyon

7.2.3 Simulation Condition

During operation, cooling towers draw a large amount of ambient air into the tower to carry out evaporative heat transfer. After receiving heat from water, air becomes heated and saturated as it absorbs water vapor, and is discharged into the ambient canyon.

In this study, the environmental condition of the 3D model is set at a condition with high RH that commonly occurs under subtropical weather condition with temperature at 17.7^{o}C and RH at 92.0% (which gives moisture content of approximately 0.0115 kgM / kgDA).

Another thing that would affect the wind flow pattern within the wind canyon is the prevailing wind velocity, which in turn affects the formation of visible plume in the region of interest. With reference to the work undertaken by Yu [Yu, 2005], five wind velocities are considered in the simulation from light wind to strong breeze as shown in Table 8.

Table 8 Different types of wind velocities and at its wind specification

Trial	Wind velocity (m/s)
Light air	0.5
	1.0
Light breeze	2.5
Gentle breeze	4.6
Moderate breeze	6.5

In this study, the purpose is to identify the impact of visible plume within the wind canyon, and the reduction of visible plume within the specified region after using the water shedding approach. Therefore, it is necessary to specify the cooling tower design on air-side and water side.

The discharge condition of the cooling tower during normal operation is made reference to the calculation carried out in Section 5.3.1.3, and additional calculation is carried out to calculate the discharge condition when the developed water shedding approach is used. Table 9 shows the two discharge air conditions.

Table 9 Conditions of cooling tower discharge, with and without use of water shedding approach

	Dry Bulb Temp (^{o}C)	Moisture Content (kgM/kgDA)	RH (%)
Prior Water Shedding	22.6	0.0177	Super-Sat
After Water Shedding	19.9	0.0144	98.7

Other boundary conditions for the CFD simulation are specified below, which include:

- Wall

  The building blocks are set as walls and assumed no thickness and adiabatic as convective and radiant heat transfer have limited impact on the flow pattern of visible plume in this study. In addition, this would allow focus to be placed on the heat transfer only between the discharge air and the air of the environment.

- Symmetry

  The side of the model is set as symmetry to ensure that the physical geometry of interest have mirrored symmetry, and assuming zero flux across the symmetry boundary during the calculation procedures.

7.2.4 Simulation Model

In this study, k-ε turbulence model is adopted for simulation as Meroney suggests that this model is acceptable for cooling tower plume analysis (Meroney, 2008), and also due to the positive validation results in **Section 5.4.3**,

In order to carry out analysis on visibility of plume, it is important to identify the moisture content level of air at any temperature of air within the wind canyon. With respect to this, the transport model in Fluent is adopted which would calculate the humidity ratio of air, thus able to identify the RH of air at any specific temperature.

7.3 Results

The prevalent wind formed a recirculation within the wind canyon due to the current domain configuration as shown in Figure 82 where height of a block is equivalent to the distance between the blocks. Figure 87 showed the flow pattern within the wind canyon where wind velocity was low with velocity of 0.5 m/s. As the velocity of the prevailing wind was not strong within the canyon and that the velocity of cooling tower was of a much higher velocity, the flow pattern within the canyon was dominated by the discharge flow of the cooling tower.

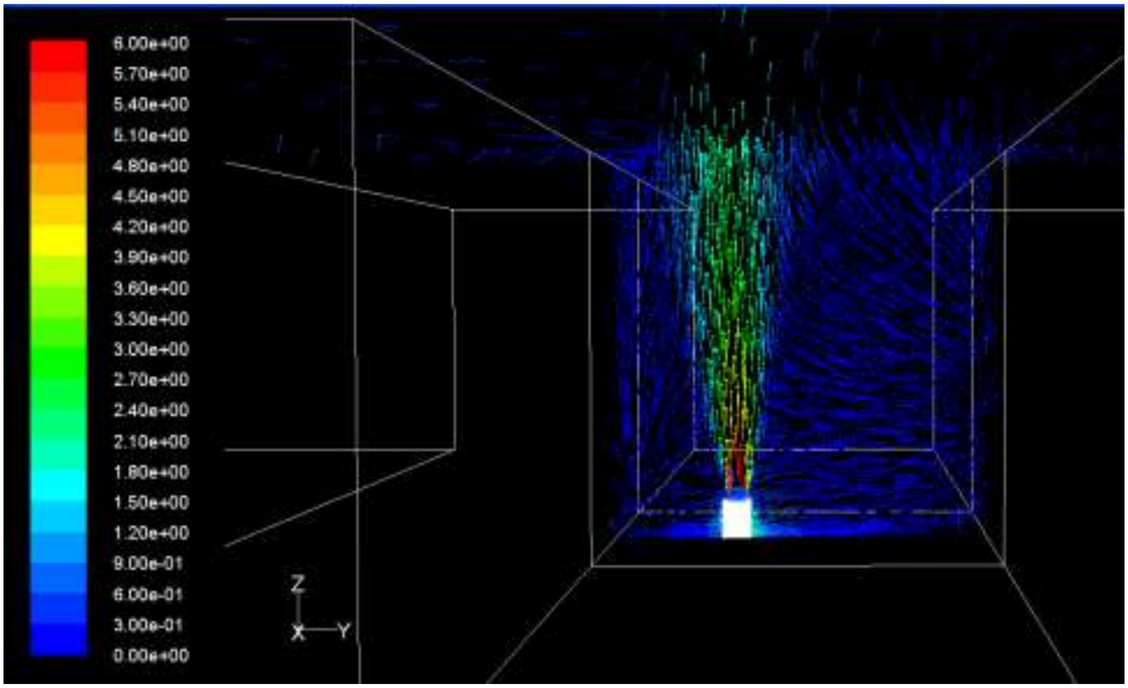


Figure 87 Velocity profile within the wind canyon under wind velocity of 0.5 m/s

In contrast, when stronger prevailing wind was blown, the flow pattern, as shown in Figure 88 and Figure 89, within the wind canyon was dominated by the wind and no longer by the discharge flow of the cooling tower.

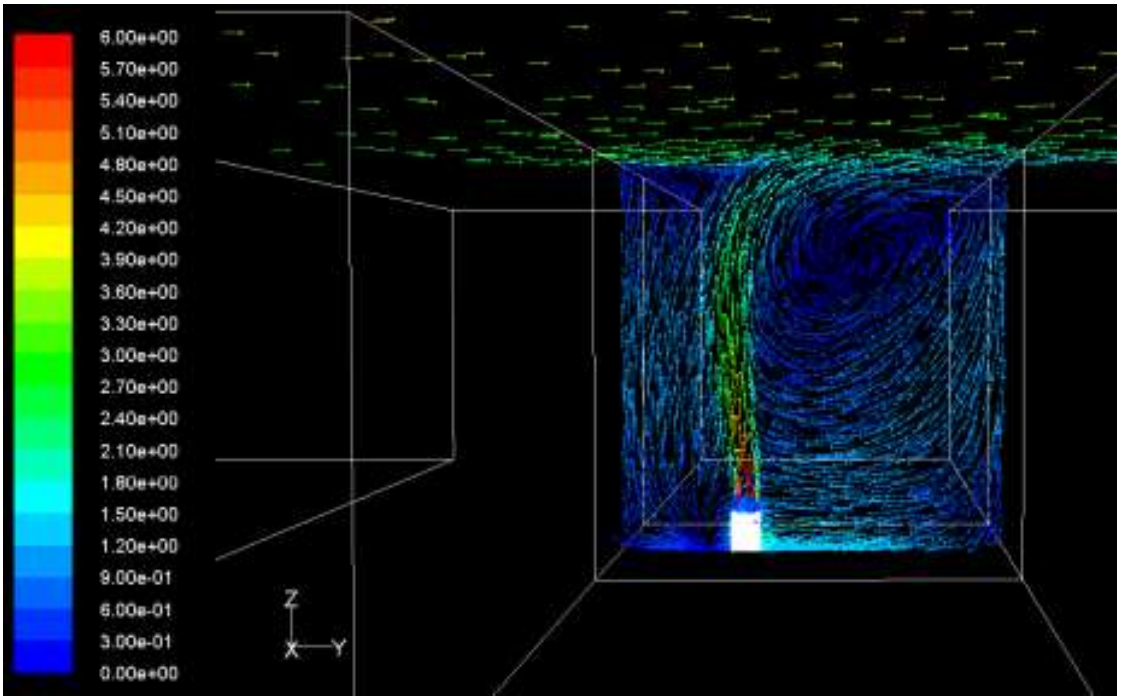


Figure 88 Velocity profile within the wind canyon under wind velocity of 6.5 m/s

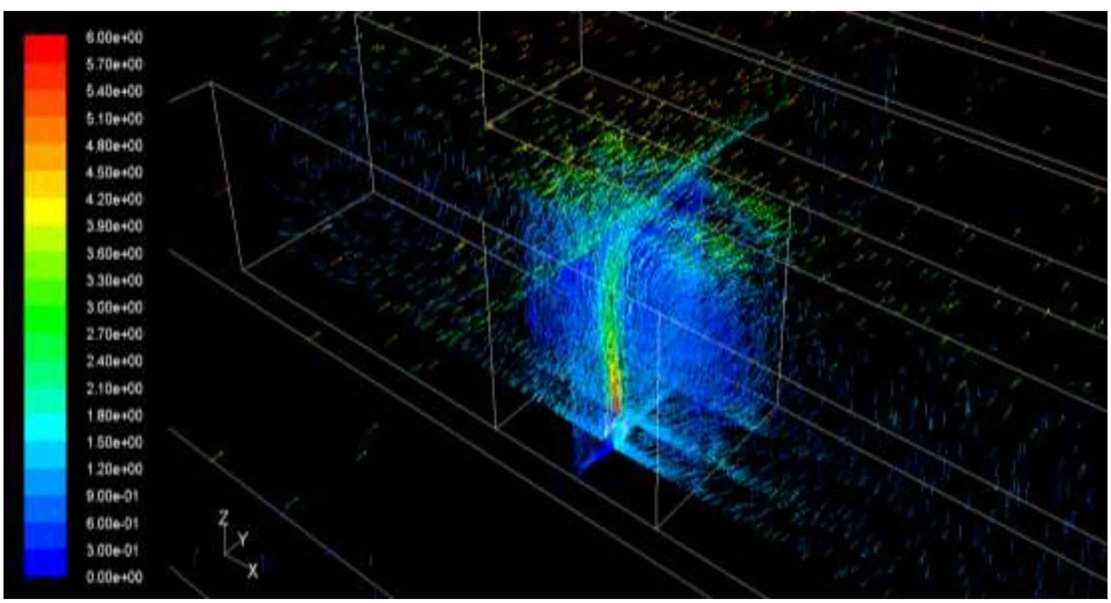


Figure 89 3D view of the wind flow pattern within the wind canyon when prevailing wind velocity is at 6.5 m/s

Given that there were five wind conditions, three different locations of cooling tower and two discharge air conditions in this study, a total of 30 simulations were carried out. Results of these cases were as shown in the following sections, and discussion was focused on the plume analysis comparison between with and without the use of the water shedding approach.

7.3.1 Cooling Tower Closes to Windward Wall of Wind Canyon (D_{ratio} = 0.25)

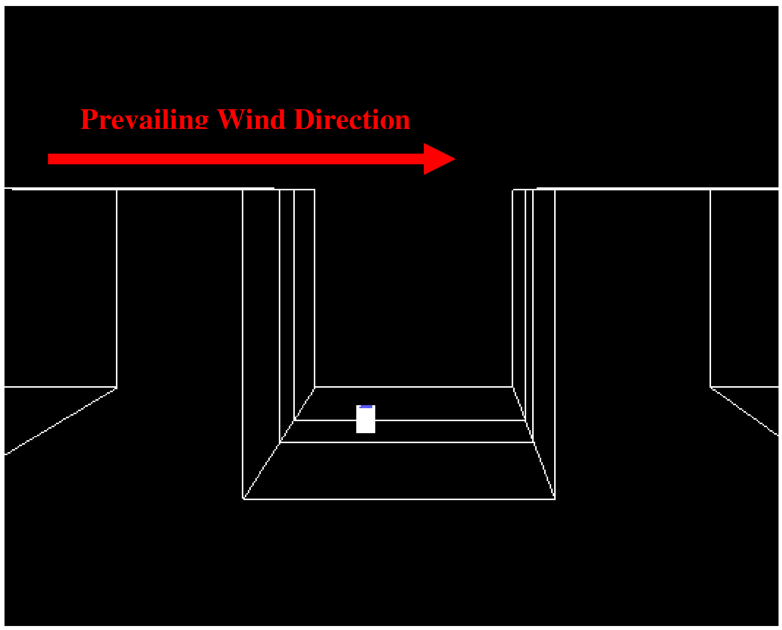


Figure 90 Configuration of the wind canyon with cooling tower closest to the windward wall

When the cooling tower was constructed nearest to the windward wall of the wind canyon, the windward wall was expected to have the greatest impact as it was closest to the cooling tower.

From the simulation result, it was shown that when the wind velocity was low, flow pattern of the visible plume would not be affected with the visible plume a distance away from the leeward wall as shown in Figure 91.

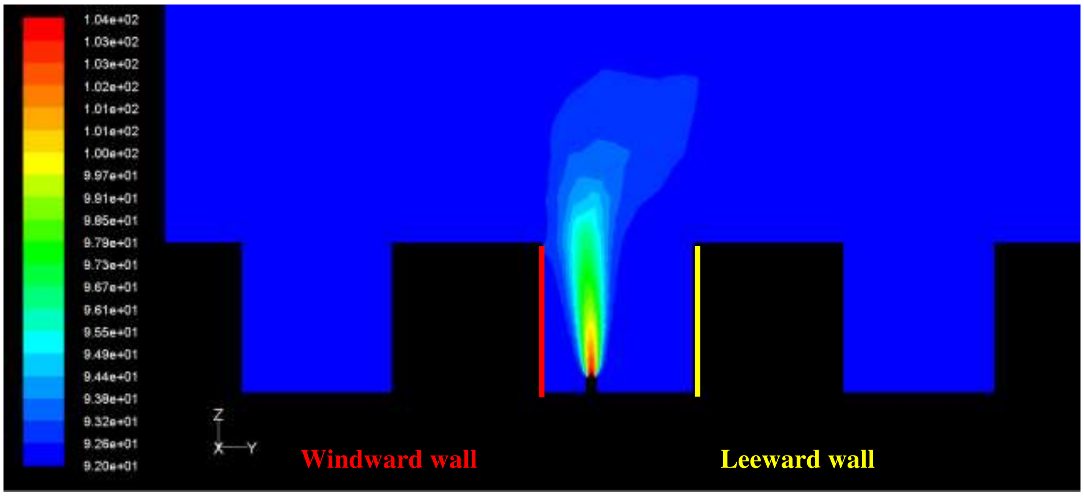


Figure 91 Visible plume within the wind canyon when wind was blowing at 0.5m/s without water shedding approach and cooling tower close to the windward wall

However, when the wind was blowing at a higher velocity, the velocity profile as indicated from CFD simulation showing the flow pattern was dominated by the wind as the discharge air was pushed towards the windward wall at the bottom of the canyon while being pushed towards the leeward wall at the top of the canyon.

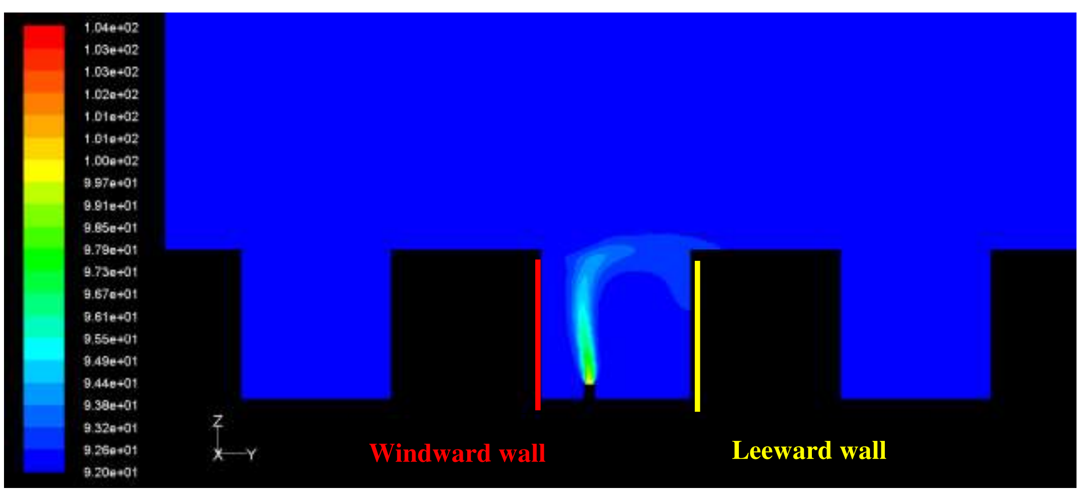


Figure 92 Visible plume within the wind canyon when wind was blowing at 6.5m/s without water shedding approach and cooling tower close to the windward wall

Table 10 showed the change in the maximum temperature and maximum moisture content at different wind condition when cooling tower was built adjacent to the windward wall. It was clearly indicated when wind velocity was

Under light wind condition with velocity at 2.5 m/s, it could be seen that the discharge of cooling tower would be pushed towards the windward wall and resulting with the maximum temperature at the windward wall slightly higher than ambient temperature by 0.4% and moisture content of 1.4% higher than ambient moisture content.

However, as wind velocity further increased to 6.5m/s, the circulating flow pattern of wind would tend to push the discharge air to the leeward wall as shown in Figure 92 and as indicated in Table 10. As a result, the maximum temperature at the windward wall would be 3.4% higher than ambient temperature and moisture content would be 3.6% higher than ambient moisture content.

Table 10 Air Condition without water shedding approach when cooling tower near windward wall

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (^{o}C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (^{o}C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.78	0.0117	92.70	17.78	0.0116	92.30
1.0	17.79	0.0117	92.74	17.79	0.0116	92.34
2.5	17.91	0.0118	93.11	17.83	0.0117	92.67
4.6	18.00	0.0119	93.33	17.92	0.0118	92.82
6.5	17.87	0.0117	92.21	18.14	0.0119	92.62

As indicated in the analysis, visible plume would occur at the discharge point as RH was 100% as shown in Figure 91 and Figure 92 right at the discharge point of the tower, and more severe when under light wind condition. In order to reduce visible plume and impact of cooling tower discharge upon both sides of the wall, the water shedding approach was used.

When the developed water shedding approach was used, the visibility of plume was reduced as shown in both Figure 93 with wind velocity at 0.5m/s and Figure 94 with wind velocity at 6.5m/s.

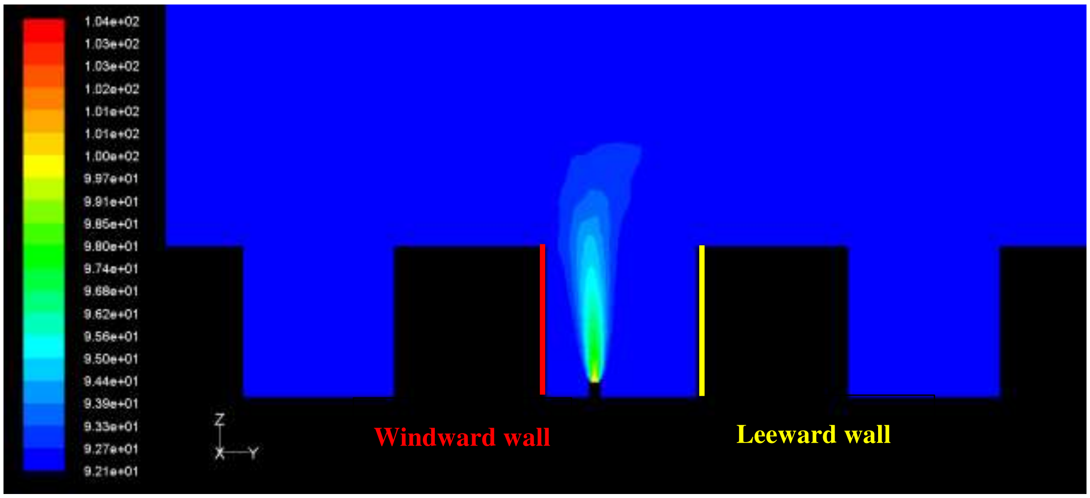


Figure 93 Visible plume within the wind canyon when wind was blowing at 0.5m/s with water shedding approach and cooling tower close to the windward wall

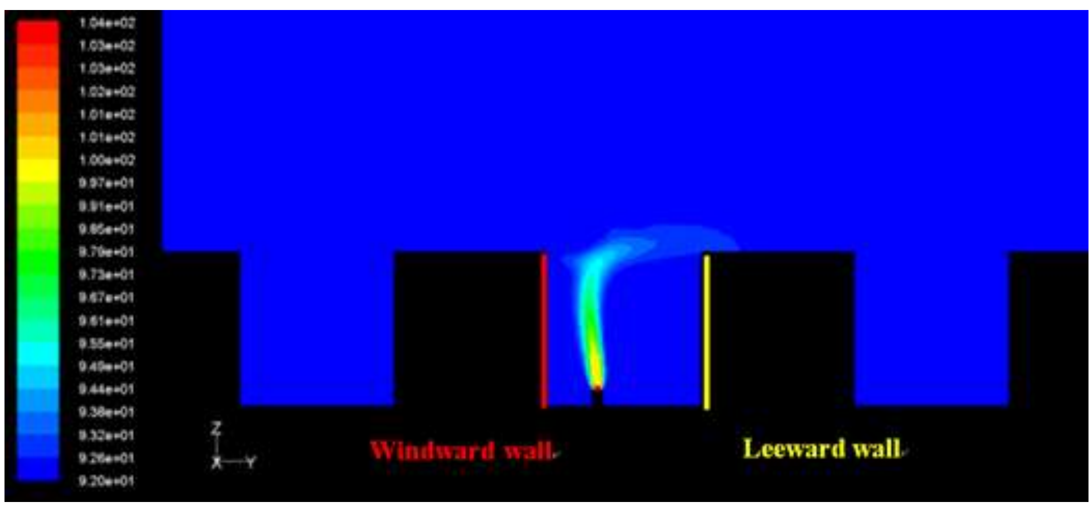


Figure 94 Visible plume within the wind canyon when wind was blowing at 6.5m/s with water shedding approach and cooling tower close to the windward wall

When the developed water shedding approach is used, the influence of discharge air on both the windward wall and leeward wall were reduced as shown in Table 11. When the wind velocity is at 0.5m/s, the temperature and moisture content at the windward wall would only be 0.3% and 1.1%

higher than the ambient conditions respectively. Similarly when wind velocity was at 6.5m/s, the temperature and moisture content at the leeward wall would only be 1.5% and 2.7% higher than the ambient conditions respectively as shown in Table 11.

The analysis showed that visible plume severity reduced and tower had less impact upon both the windward wall and the leeward wall when the developed water shedding approach was used.

Table 11 Air Condition with water shedding approach when cooling tower near windward wall

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.75	0.0116	92.50	17.73	0.0116	92.26
1.0	17.77	0.0116	92.55	17.74	0.0116	92.31
2.5	17.83	0.0117	92.75	17.79	0.0116	92.47
4.6	17.87	0.0117	92.82	17.86	0.0117	92.65
6.5	17.80	0.0116	92.23	17.97	0.0118	92.72

7.3.2 Cooling Tower Closes to Centre of Wind Canyon (D_{ratio} = 0.50)

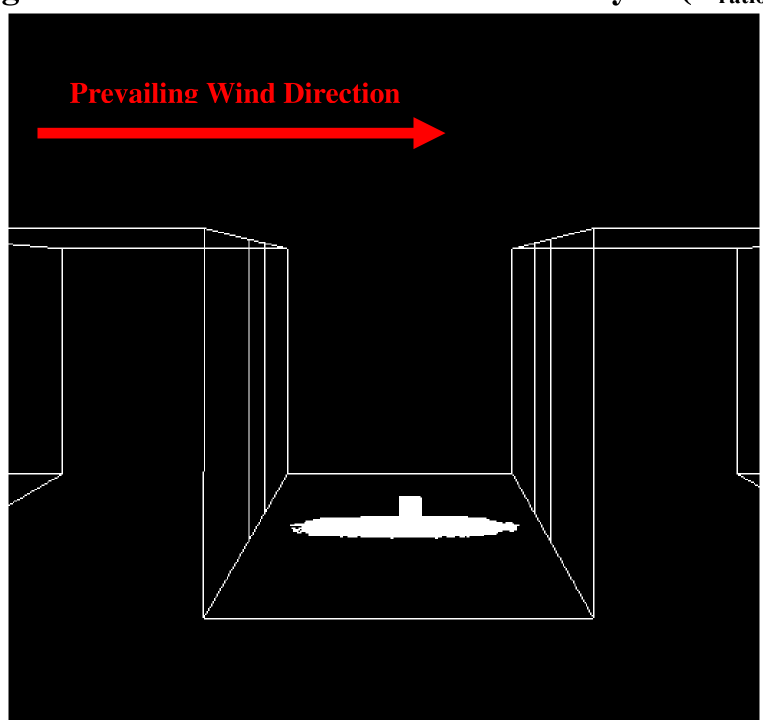


Figure 95 Configuration of the wind canyon with cooling tower is at the centre

When cooling tower was placed at the centre of the wind canyon, there were a great distances between the cooling tower and the windward and leeward walls. As could be seen in Figure 96, the visibility of plume would be blown upwards and there would be little change in direction when wind velocity was at 0.5m/s.

It was shown that under such condition, the temperature and the moisture content near the windward wall increased by 0.2% and 0.9% respectively compared to the ambient air conditions. As for the leeward wall, the temperature and the moisture content increased by 0.4% and 1.2% respectively when compared to the ambient air condition.

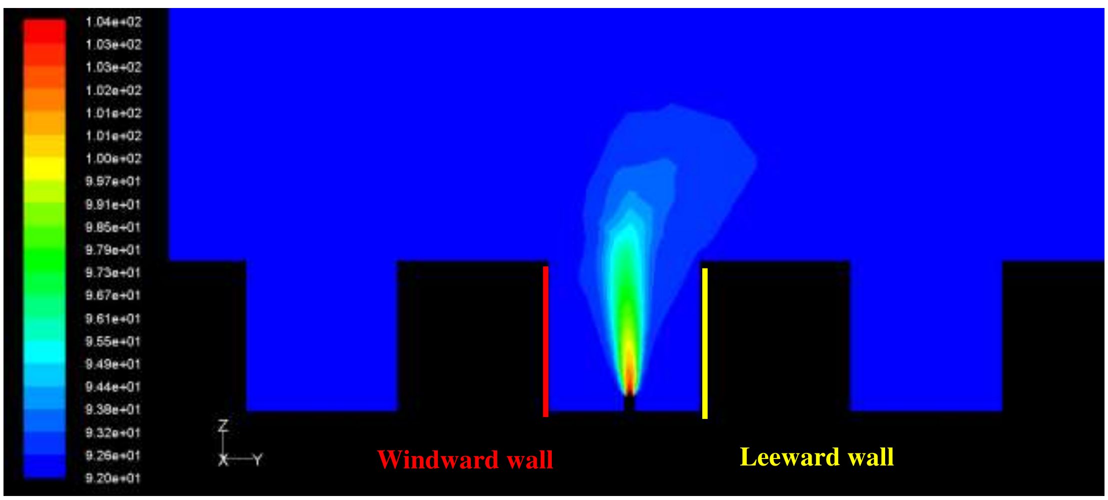


Figure 96 Visible plume within the wind canyon when wind was blowing at 0.5m/s without water shedding approach and cooling tower at centre of canyon

When wind velocity increased, the flow pattern within the canyon would tend to push the discharge air towards the leeward wall as shown in Figure 97 (Moderate breeze condition, 6.5m/s wind velocity). Under this moderate breeze condition, temperature at the leeward wall would be 3.3% higher than ambient air condition while moisture content at the leeward wall would be 6.0% higher than ambient air condition.

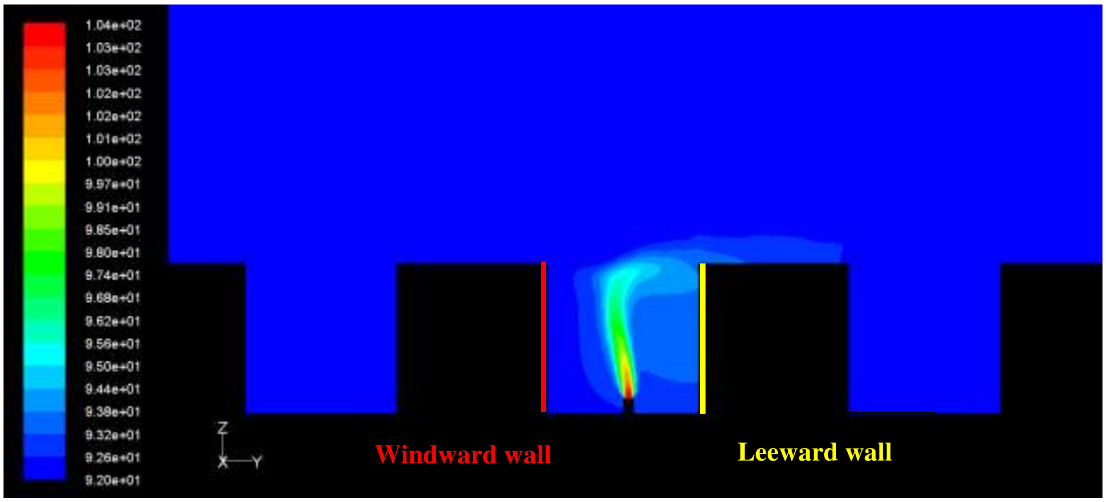


Figure 97 Visible plume within the wind canyon when wind was blowing at 6.5m/s without water shedding approach and cooling tower at centre of canyon

Table 12 Air Condition without water shedding approach when cooling tower at centre of canyon

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.74	0.0116	92.45	17.76	0.0116	92.57
1.0	17.76	0.0116	92.28	17.78	0.0116	92.20
2.5	17.73	0.0116	92.21	17.85	0.0117	92.73
4.6	17.78	0.0116	92.39	18.05	0.0119	93.37
6.5	17.81	0.0117	92.46	18.29	0.0122	93.79

As indicated in the analysis, visible plume would occur at the discharge point as RH was 100% as shown in Figure 96 and Figure 97. In order to reduce visible plume and impact of cooling tower discharge upon both sides of the wall, the developed water shedding approach was used.

When the developed water shedding approach was used, the visibility of plume was clearly reduced as shown in both Figure 98 with wind velocity at 0.5m/s and Figure 99 with wind velocity at 6.5m/s.

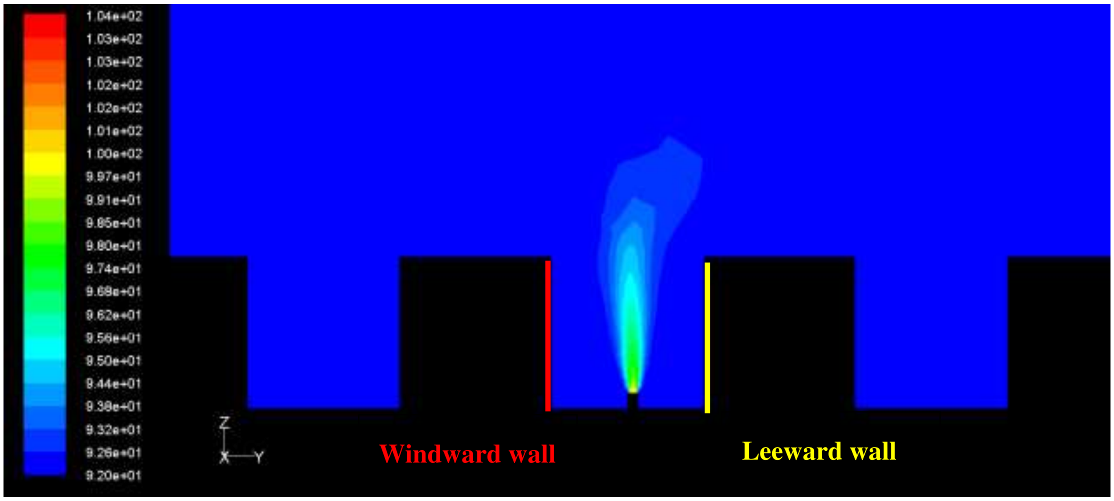


Figure 98 Visible plume within the wind canyon when wind was blowing at 0.5m/s with water shedding approach and cooling tower at centre of canyon

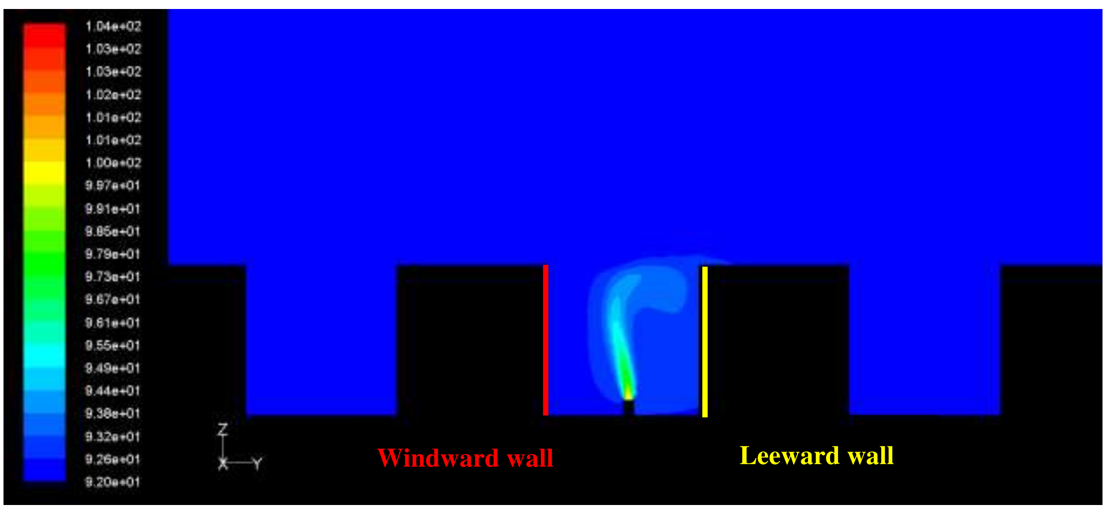


Figure 99 Visible plume within the wind canyon when wind was blowing at 6.5m/s with water shedding approach and cooling tower at centre of canyon

Under a wind velocity of 6.5m/s, the temperature and moisture content would show an increase of 0.5% and 1.1% compared to the ambient air conditions respectively at the windward wall, and the temperature and the moisture content would increase by 1.6% and 3.2% respectively compared to the ambient air conditions respectively at the leeward wall.

Table 13 shows the maximum temperature and maximum moisture content at the windward wall and at the leeward wall when the water shedding approach was implemented. It also indicated that the impact of the cooling tower discharge would not be less than the case when water shedding approach was not implemented

Table 13 Air Condition with water shedding approach when cooling tower at centre of canyon

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (^{o}C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (^{o}C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.72	0.0116	92.25	17.74	0.0116	92.37
1.0	17.72	0.0116	92.23	17.74	0.0116	92.34
2.5	17.73	0.0116	92.26	17.80	0.0117	92.53
4.6	17.75	0.0116	92.29	17.94	0.0118	92.95
6.5	17.78	0.0116	92.38	17.99	0.0119	93.89

7.3.3 Cooling Tower Closes to Windward Wall of Wind Canyon (D_{ratio} = 0.75)

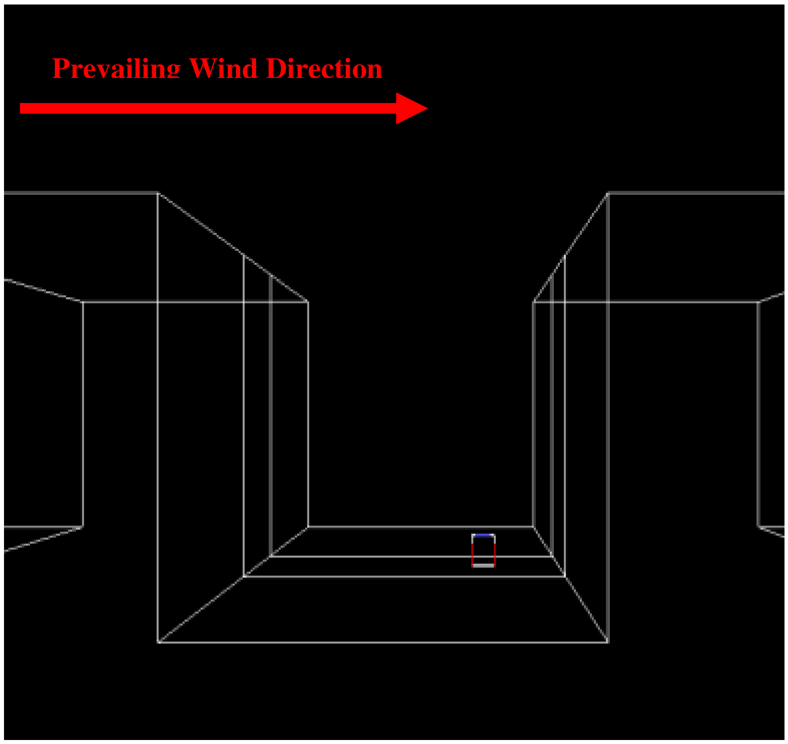


Figure 100 Configuration of the wind canyon with cooling tower close to the leeward wall

When a cooling tower was placed near the leeward wall with a wind velocity of 0.5m/s, the upper zone of the leeward wall would be affected by the discharge of the cooling tower as shown in Figure 101. Under this condition, the temperature reading at the leeward wall was 2.5% higher than ambient air temperature and moisture content reading at the leeward wall was 5.0% more than moisture content of ambient air.

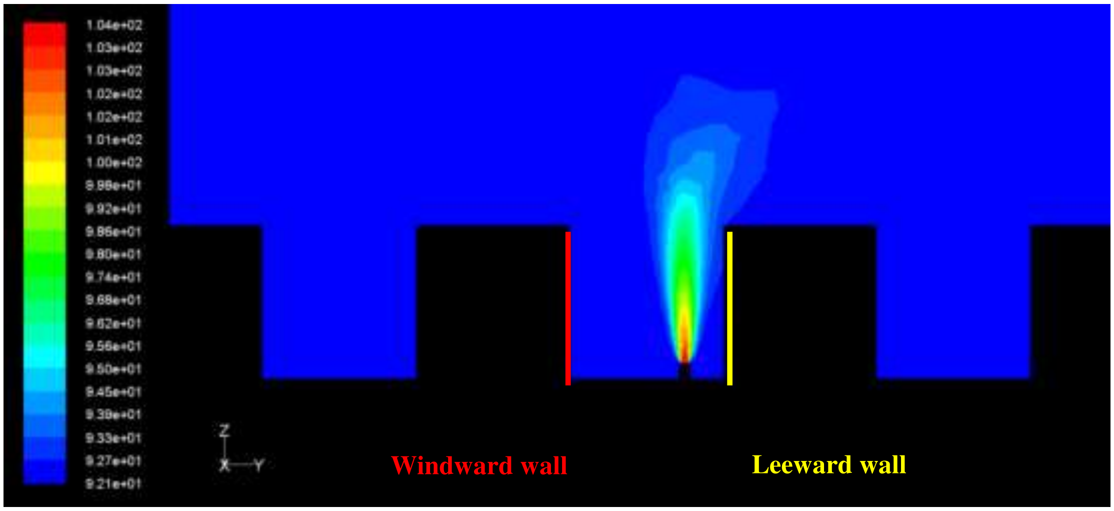


Figure 101 Visible plume within the wind canyon when wind was blowing at 0.5 m/s without water shedding approach with cooling tower close to the leeward wall

As wind velocity increased, the upwards airflow pattern of discharge air was pushed towards the leeward wall as shown in Figure 102. Under this condition, temperature at the leeward wall would be 4.0% higher than the ambient temperature and moisture content at the leeward wall would be 7.2% higher than the ambient moisture content.

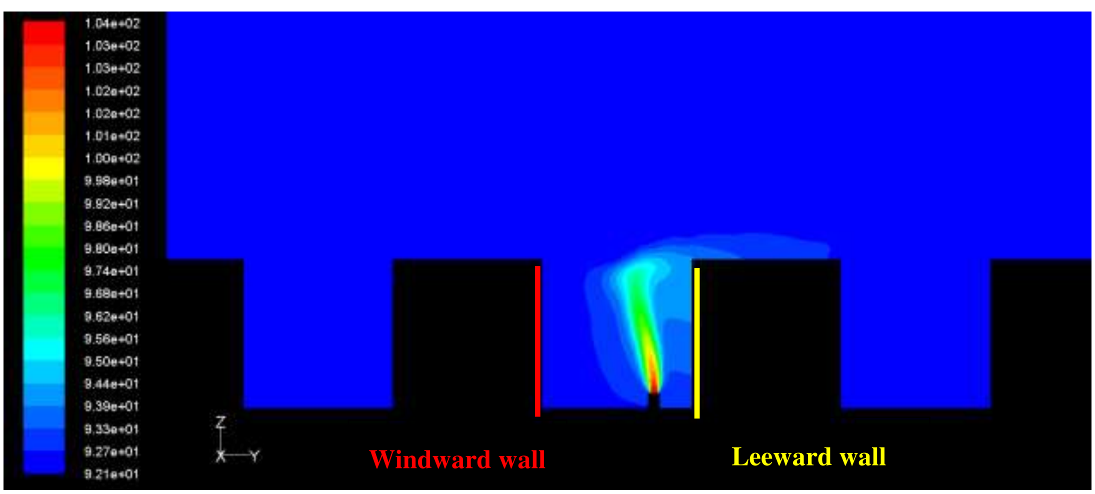


Figure 102 Visible plume within the wind canyon when wind was blowing at 6.5m/s without water shedding approach with cooling tower close to the leeward wall

Table 14 Air Condition without water shedding approach when cooling tower near leeward wall

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (^oC)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (^oC)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.72	0.0115	92.16	18.15	0.0121	93.70
1.0	17.72	0.0116	92.19	18.16	0.0121	93.71
2.5	17.72	0.0116	92.17	18.18	0.0121	93.84
4.6	17.77	0.0116	92.35	18.28	0.0122	94.09
6.5	17.82	0.0117	92.51	18.40	0.0123	94.15

The developed Water shedding approach was used to reduce visible plume and the impact of discharge air upon the leeward wall. At calm wind condition where prevailing wind velocity was at 0.5m/s, the temperature at the leeward wall would be 0.3% higher than the ambient temperature and the moisture content would be 2.6 higher than the ambient moisture content level. This shows that the water shedding approach would be effective to reduce the impact of cooling tower upon the leeward wall within a canyon.

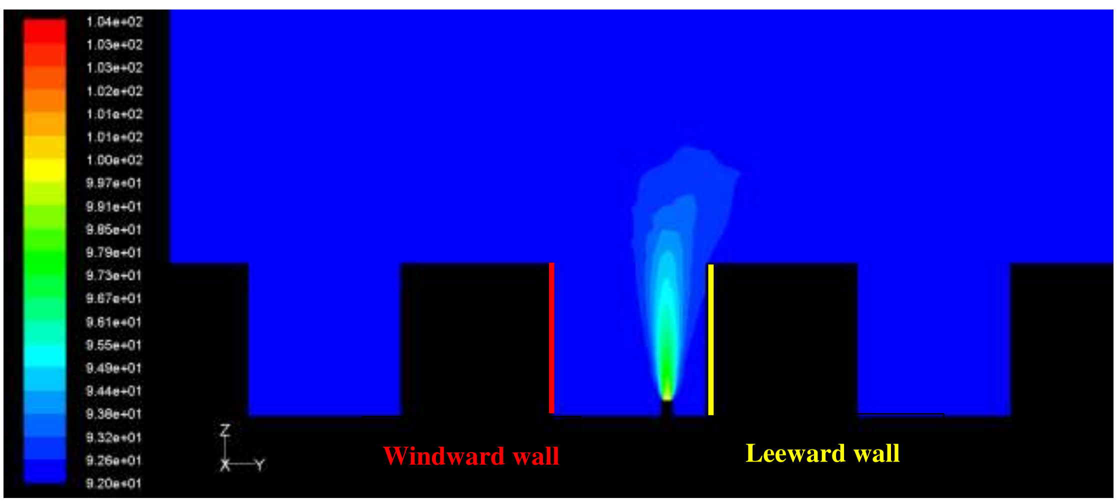


Figure 103 Visible plume within the wind canyon when wind is blowing at 0.5 m/s with water shedding approach with cooling tower close to the leeward wall

When the prevailing wind reached 6.5m/s, temperature at the leeward wall would be 2.1% higher than the ambient temperature and the moisture content at the leeward wall would be 4.0% higher than the ambient moisture content. This showed a reduction of visible plume and discharge air upon the leeward wall with the use of water shedding approach, which comparison of air properties under different wind conditions with and without use of water shedding approach could refer to Table 15.

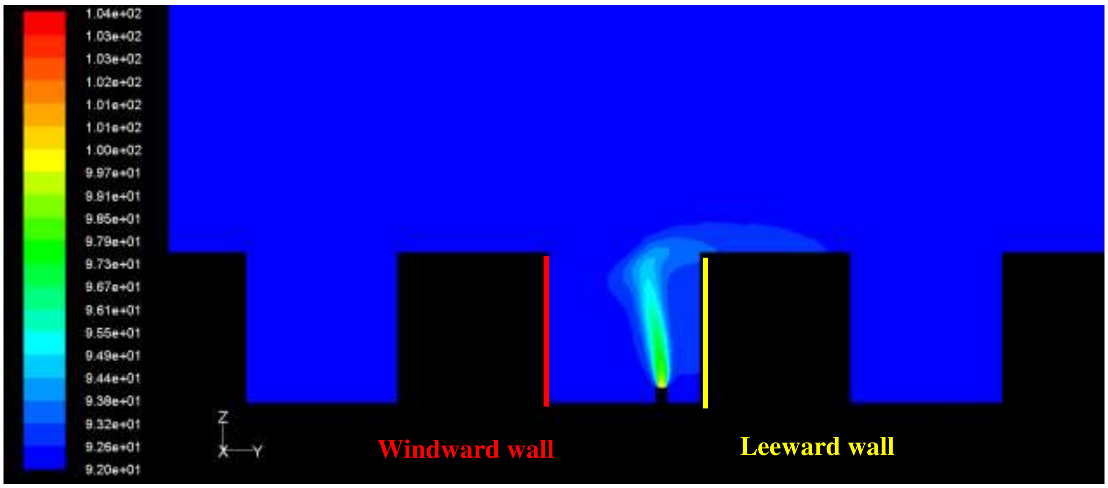


Figure 104 Visible plume within the wind canyon when wind is blowing at 6.5m/s with water shedding approach with cooling tower close to the leeward wall

Table 15 Air Condition with water shedding approach when cooling tower near leeward wall

Wind velocity (m/s)	Windward Wall			Leeward Wall		
	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)	Max. Temp (°C)	Max. Moisture Content (kgM/kgDA)	Max. RH (%)
0.5	17.71	0.0116	92.13	17.76	0.0118	92.70
1.0	17.72	0.0116	91.14	17.81	0.0118	92.85
2.5	17.73	0.0116	92.16	17.97	0.0119	93.14
4.6	17.74	0.0116	92.26	18.02	0.0119	93.28
6.5	17.79	0.0116	92.47	18.07	0.0120	93.27

7.4 Overall Results

Table 16 showed all the results of CFD simulation at windward wall and leeward wall for the following conditions

- Cooling tower at different location
- Different Wind Velocity
- With and without the water shedding approach

It was found that when the developed water shedding approach is used, visible plume would be reduced as well as the spread of discharge air at the immediate environment. It was also shown from CFD simulation results that there was a maximum reduction in temperature of 0.33 ^{o}C and maximum moisture content of 0.0003 kgDA/kgM.

Table 16 Air Condition with water shedding approach when cooling tower near leeward wall

		Windward Wall		Leeward Wall	
		No Water Shedding Approach	Water Shedding Approach	No Water Shedding Approach	Water Shedding Approach
CT Close to Windward Wall	Calm Air (0.5 m/s)	17.78 °C 0.0117 kgDA/kgM	17.75 °C 0.0116 kgDA/kgM	17.75 °C 0.0116 kgDA/kgM	17.73 °C 0.0116 kgDA/kgM
	Moderate Wind (6.5 m/s)	17.87 °C 0.0117 kgDA/kgM	17.80 °C 0.0116 kgDA/kgM	18.14 °C 0.0119 kgDA/kgM	17.97 °C 0.0118 kgDA/kgM
CT at Centre of Canyon	Calm Air (0.5 m/s)	17.74 °C 0.0116 kgDA/kgM	17.72 °C 0.0116 kgDA/kgM	17.76 °C 0.0116 kgDA/kgM	17.74 °C 0.0116 kgDA/kgM
	Moderate Wind (6.5 m/s)	17.81 °C 0.0117 kgDA/kgM	17.78 °C 0.0116 kgDA/kgM	18.29 °C 0.0122 kgDA/kgM	17.99 °C 0.0119 kgDA/kgM
CT Close to Leeward Wall	Calm Air (0.5 m/s)	17.72 °C 0.0116 kgDA/kgM	17.71 °C 0.0116 kgDA/kgM	18.15 °C 0.0121 kgDA/kgM	17.76 °C 0.0118 kgDA/kgM
	Moderate Wind (6.5 m/s)	17.82 °C 0.0117 kgDA/kgM	17.79 °C 0.0116 kgDA/kgM	18.40 °C 0.0123 kgDA/kgM	18.07 °C 0.0120 kgDA/kgM

7.5 Conclusions

Visible plume is a major concern to the public as many people are concerned with the environmental and health impact upon them. This is of even more concerns when cooling tower is placed on the street level that is in close proximity to the surrounding buildings and pedestrian accessible zones, especially when the cooling towers were placed within an urban canyon (zone between buildings).

In this chapter, study was carried out to identify the impact of cooling tower discharge towards the adjacent environment within a canyon. With this respect, a 3D model was constructed with tetrahedral meshes over 1.6 – 1.8 million. The cooling towers were located at differently within the canyon and under different wind conditions with prevailing wind velocity ranging from 0.5m/s – 6.5m/s.

In the analysis, it was shown that when cooling towers were operating at normal condition, visibility of plume would appear under moist air condition. In addition, the windward wall and the leeward wall within the canyon would be affected by the cooling tower discharged caused these area with raised temperature and level of moisture content.

The water shedding approach was developed in order to reduce visible plume and the spread of discharge air within the canyon. CFD Simulations were carried out with different cases, where cooling towers were placed at different locations, change in prevailing wind velocity as well as with and without the use of the developed water shedding approach.

It was found in this study that the impact of cooling tower discharge was reduced in both severity and the impact the discharge had to the immediate environment. From the CFD simulation, it shows that when the developed visible plume abatement was used, the maximum temperature within the canyon was reduced by 0.33 ^{o}C and maximum moisture content was reduced by 0.0003 kgDA/kgM.

Chapter 8 – Development of a Management Platform for the Cooling Tower

8.1 Bridge the Gap Between Research and Industry

In this thesis, cooling tower was classified as one of the most important equipment for building as cooling tower is responsible for effective heat rejection in order to maintain all building cooling equipment in good performance and maintaining an excellent indoor environmental condition. However, cooling tower discharge can become a nuisance to the adjacent environment with health impact and visual concerns to the public (Havey, 2008)

In order to calculate the calculate the visible plume abatement effect and cooling tower discharge had upon the surrounding environment, the calculation method for cooling tower would be extremely crucial.

Multiple cooling tower performance calculation methodologies were developed, of which the Poppe Approach was more sophisticated and more accurate. However, as the Poppe Approach was a complicated model, cooling tower manufacturers would tend to use the less complicated Merkel Approach.

In order to bridge the gap between academic and building services engineers, author has designed and constructed a web-platform for cooling tower. The web-platform for cooling tower is called the Cooling Tower Manager, and it consists of different information, such as the theory of cooling tower, cooling tower calculator (Poppe Approach), visible plume analysis and research references. With this Cooling Tower Manager, the author can maximize his research output and share the academic findings with the industry, to provide the industry a user friendly and easily accessible platform to conduct quick analysis on visible plume abatement to reduce the visible plume occurrence as well as understanding the impact of visible plume to its immediate environment.

In the design of the cooling tower web-platform, the focus was to transform the research outputs into a user-friendly tool that could be used by any person. The development of this web-platform was aimed at collecting a large database to serve for future use with the intent to produce a total solution for the operation and maintenance for building system with cooling tower. The ultimate goal of this web-platform was to achieve harmonization between building health and sustainability, to push the level of sustainability to another level. This web-platform of cooling tower could achieve the target because it would provide wider knowledge for the users to inform people more about these towers and allow them to understand how to operate cooling towers efficiently and accurately.

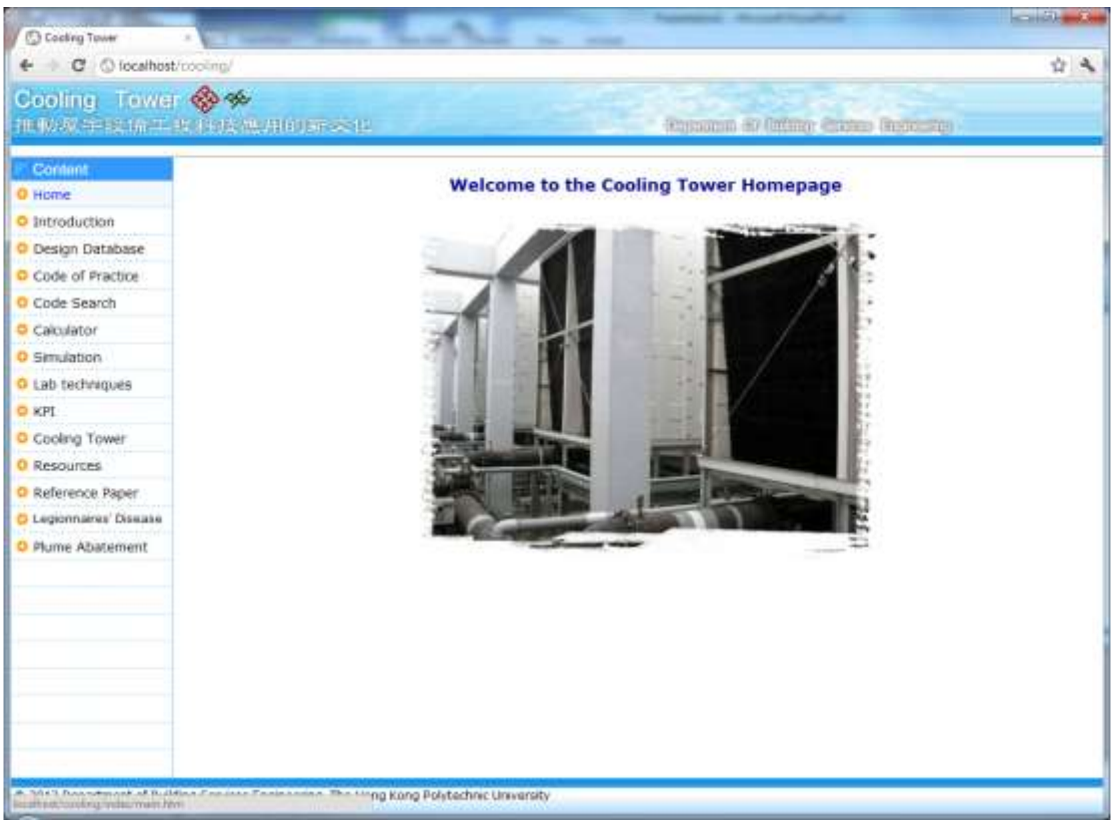


Figure 105 Front page of Cooling Tower web-platform

A wide range of useful knowledge of cooling tower was compiled into this web-platform, which the knowledge was categorized and separated into three main groups as shown below:

- Basic understanding of cooling tower and related operating/health issues
- Checklist of Cooling Tower COP
- Mathematical Modeling of cooling towers

8.1.1 Basic Knowledge

The first part of the cooling tower web-platform was to provide a walk-through of cooling tower on the basic fundamental of cooling towers with respect to the use of the building equipment and the thermodynamic when air and water exchange heat within the tower during operation.

A brief introduction for the cooling tower was provided in the web-platform as shown in Figure 106, which explained the purpose of a cooling tower, the history of cooling tower in Hong Kong, the heat transfer fundamental of evaporative cooling occurs within the cooling tower and the health impact of the cooling tower discharge air. This brief introduction would provide readers to have a higher understanding on the basic knowledge of cooling tower and would allow them to understand the importance of it in building to maintain a comfortable indoor environment for building occupants.

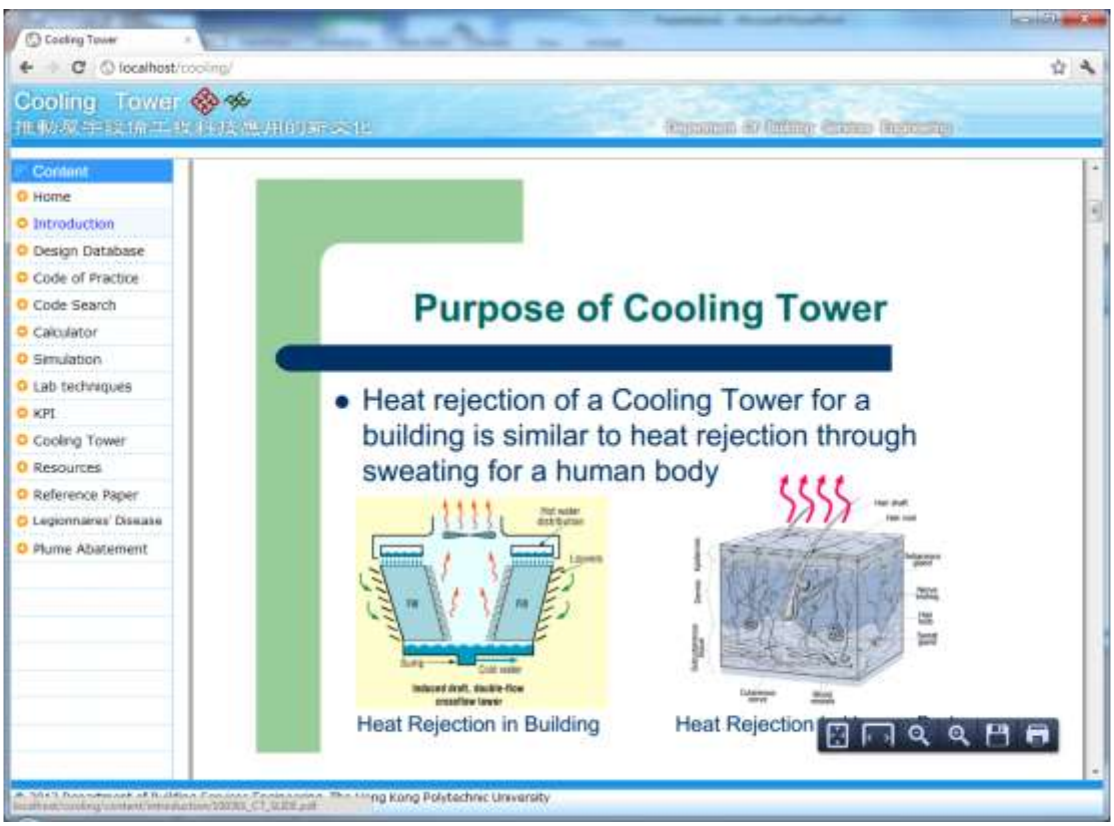


Figure 106 Educational of the web-platform of cooling tower

Besides the general information of a cooling tower, the web-platform also could provide in-depth information of cooling tower to the users. This included the COP of the cooling tower published by EMSD that consist of different requirement to attain cooling tower permit, such as the minimum distance between cooling tower and inlet louvers.

In order to enhance the readability and find information required in COP and allow for easy information retrieval, the COP was separated into different sections according to the different subjects as shown in Figure 107.

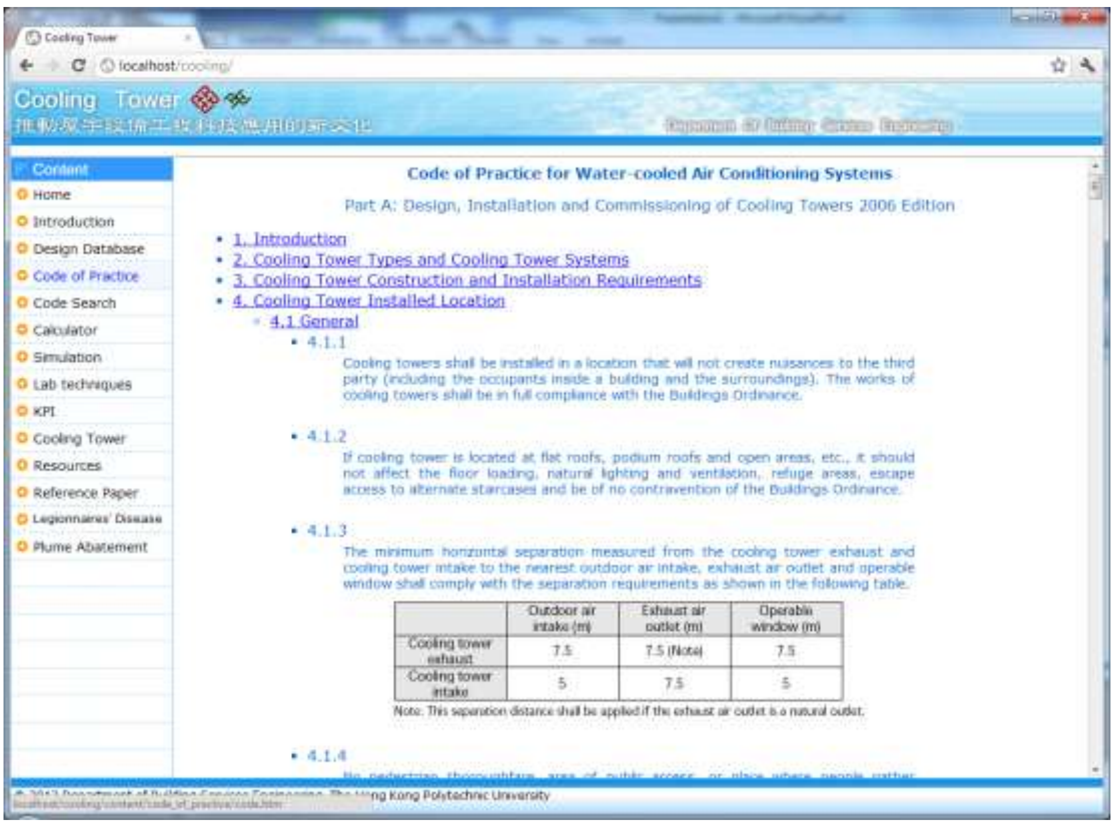


Figure 107 CoP of cooling tower with enhanced readability

The website was also developed with the aim to increase interaction with cooling tower within the industry, other industrial sources (be it manufacturer or general information from other industrial party) related to cooling towers were also included in the web-platform as shown in Figure 108 to save the users' time in finding the information themselves.

Figure 108 Other sources on the internet related to cooling tower

The aim of the web-platform was to increase understanding on cooling tower; therefore, the health impact that cooling tower had on people and the society were included. As could be seen in Figure 109, the official statistics and papers published related to Legionnaires' Disease were incorporated into the web-platform to increase the awareness of the users upon cooling tower. With these incorporated information, it would assist users to adopt more safety measures to increase protection against the potential spread of legionella.

Figure 109 Information on Legionnaires' Disease

The web-platform could provide the basic molecular biology of legionella and the associated laboratory techniques currently available in the world that could identify legionella from water samples collected from cooling tower as shown in Figure 110.

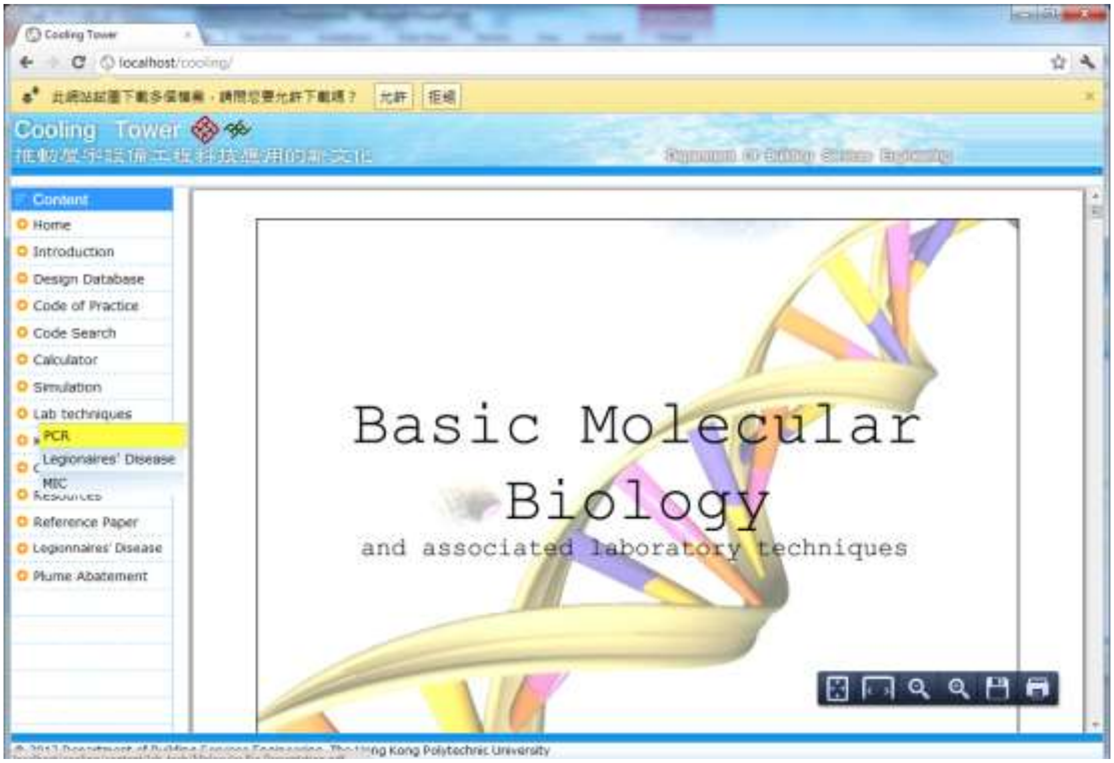


Figure 110 Molecular Biology and Laboratory techniques related to Legionnella

8.1.2 Checklist of Cooling Tower COP

Although COP was available to provide requirements and instructions for proper installation of cooling tower; however, the informative COP documents would consume time for building designer and manufacturer to ensure the installation of cooling tower would comply to government requirement.

With this respect, a user-friendly checklist based on the COP was prepared and incorporated into the web-platform as shown in Figure 111. The checklist was in a format of questionnaire and with options for user to click on as shown in Figure 112. The benefit of the checklist on this web-platform was not only time saving, but would also allow user to be familiarized with cooling tower design and how to design a cooling tower plant efficiently and effectively.

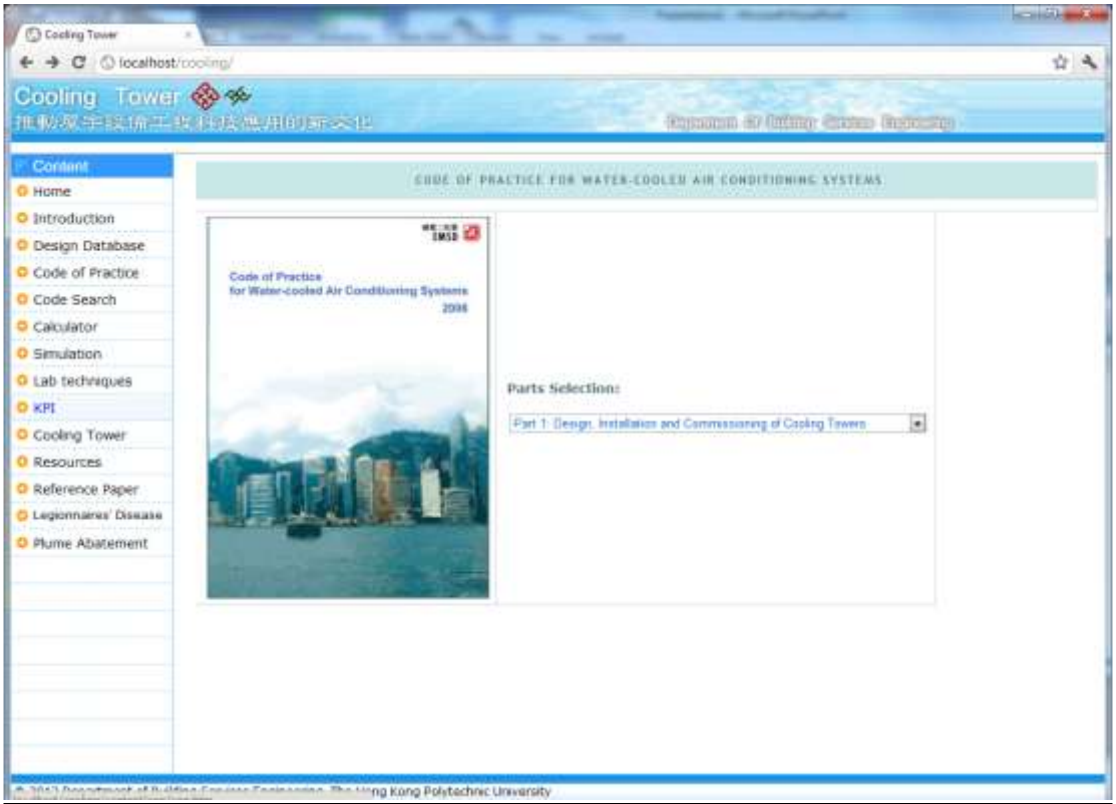


Figure 111 Front page of the checklist for the CoP

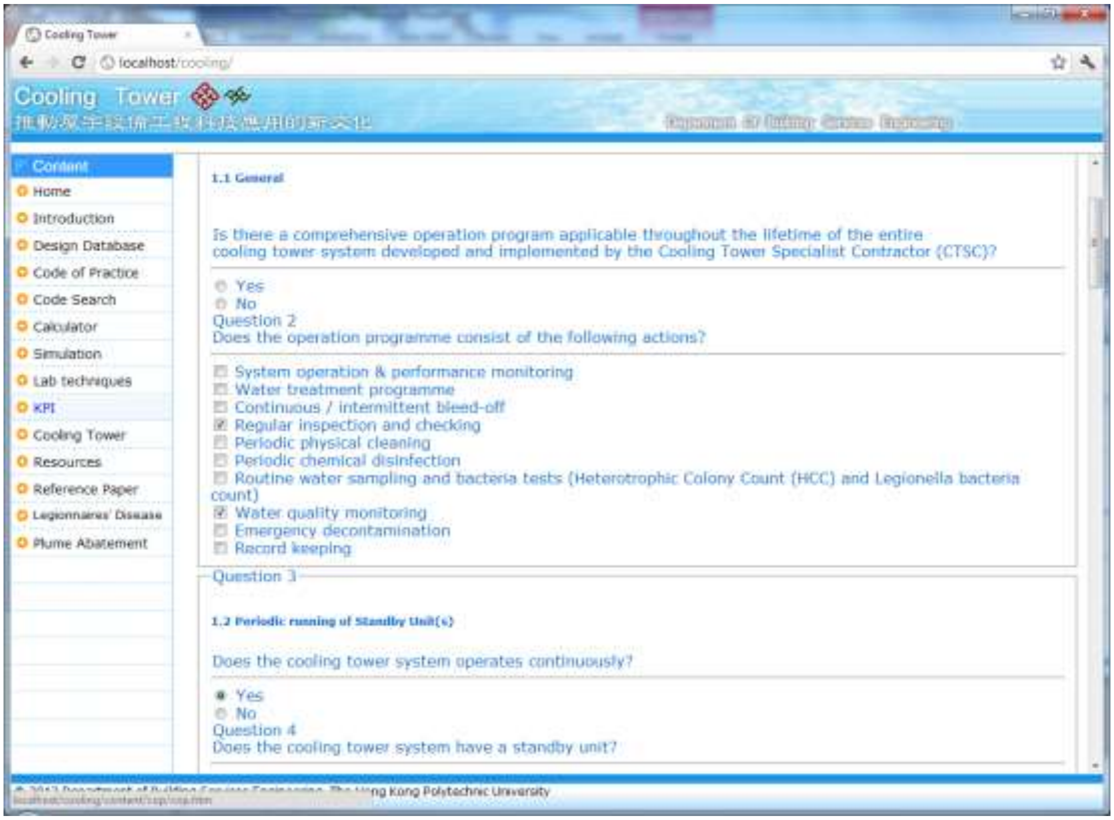


Figure 112 CoP checklist in a question format

8.1.3 Mathematical Modeling

Another successful function of the web-platform would be the cooling tower performance calculator, as well as the visible plume analyzer, based on the sophisticated Poppe Approach. Based on the validation approach carried out in Chapter 5, the calculator would be highly accurate for mechanical cross-flow cooling towers.

The idea of designing this calculator interface was its user-friendliness. The calculator would separate into three categories, namely the calculation approach, data input and plume evaluation (results).

Figure 113 shows the interface of the cooling tower calculator.

8.1.3.1 Calculation Approach

The calculation approach was to allow users to desirable method to carry out calculation for cooling tower, with the grid interval that could be adjusted by users. The more grid intervals would results in higher accuracy; however, time consumption for calculation would increase significantly (refer to Chapter 6 for comparison between grid size and calculation accuracy). Secondly, user could choose either using water outlet temperature or use the Merkel approach to predict water outlet condition in the calculation, whereas the air condition could be selected by either the RH or wet bulb temperature of the inlet air.

8.1.3.2 Data Input

This section was where the parameters of air inlet and water inlet were inputted (flow rate and temperature), as well as the location of the cooling tower (latitude) and the heat source to eliminate visible plume if there were visible plume (where wet bulb temperature was equal or less than dew point temperature at a specific dry bulb temperature). This would allow the user to calculate the discharge air condition under a specific environmental condition (air) at a specific temperature and flow rate of water.

8.1.3.3 Plume Evaluation (Results)

The last section of the calculator interface was to show the results in both graphical form and numerical form as shown in Figure 113. The numerical values would be very detailed, yet the graphical results would provide a more user-friendly display for user who had some understanding on psychometric chart to identify the discharge air condition immediately. The results also included the evaluation of visible plume analysis. For example, if heat source was used to mix with discharged supersaturated air (Figure 113); the graphical results would then show the air condition along the blue line with different flow rate of heat source provided for the mixing. The user could alternatively choose to increase the flow rate of air to reduce the visibility of plume.

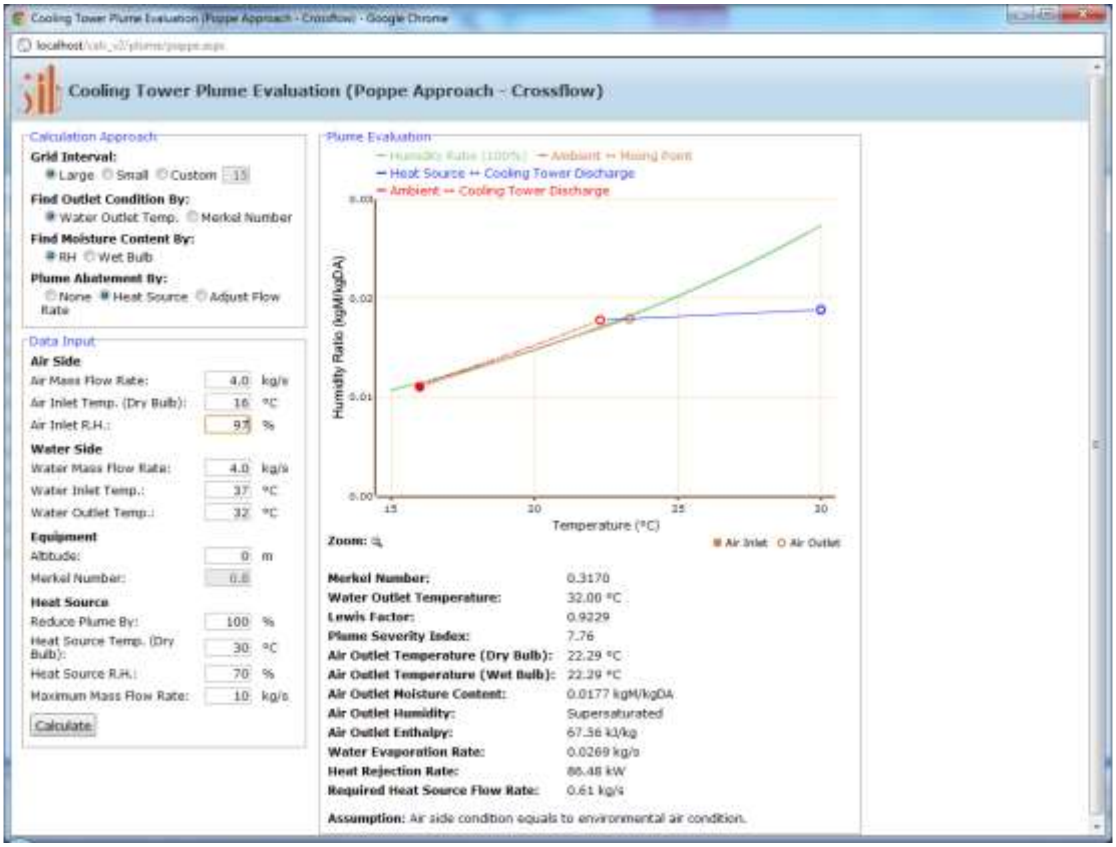


Figure 113 Cooling Tower Calculator (with visible plume & visible plume abatement)

8.1.4 Cooling Tower Graphical Results

Another feature of the web-platform was the database of 3D simulations of various scenarios. This would be beneficial for user to identify the flow pattern graphically of cooling under different natural wind condition as shown in Figure 114.

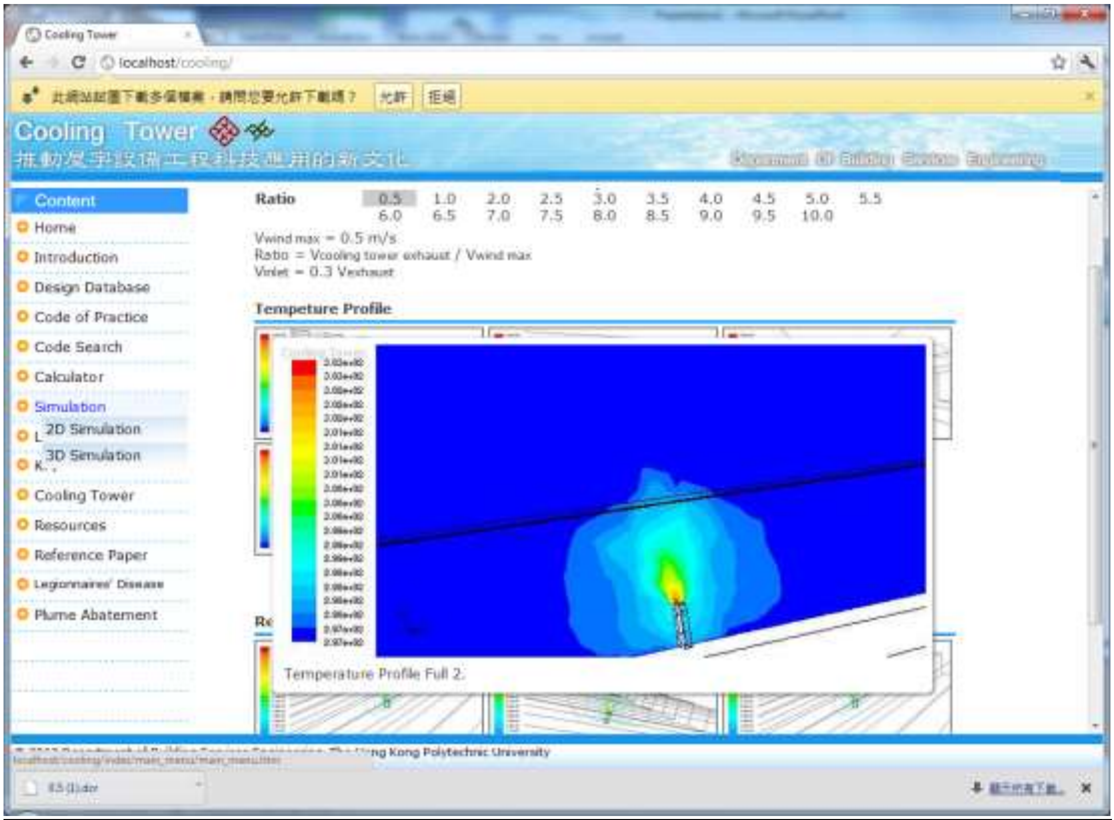


Figure 114 Static graphical results of flow pattern of cooling tower discharge

Furthermore, the web-platform could show the impact of visible plume and the effect of the effectiveness of visible plume abatement at a site of interest in a transient graphical form based on the calculation approach proposed as abovementioned. Figure 115 to Figure 117 were a set of diagrams extracted from a video that could be downloaded from the web-platform showing the effect under three different scenarios of cooling tower for a commercial cooling tower plant. The three scenarios were the occurrence of visible plume under a humid climatic condition, 100% visible plume abatement operation mode and 50% visible plume abatement operation mode. The benefit of using the transient graphical approach to provide results was aimed to enhance the user's understanding of different operation mode for visible plume abatement purpose.

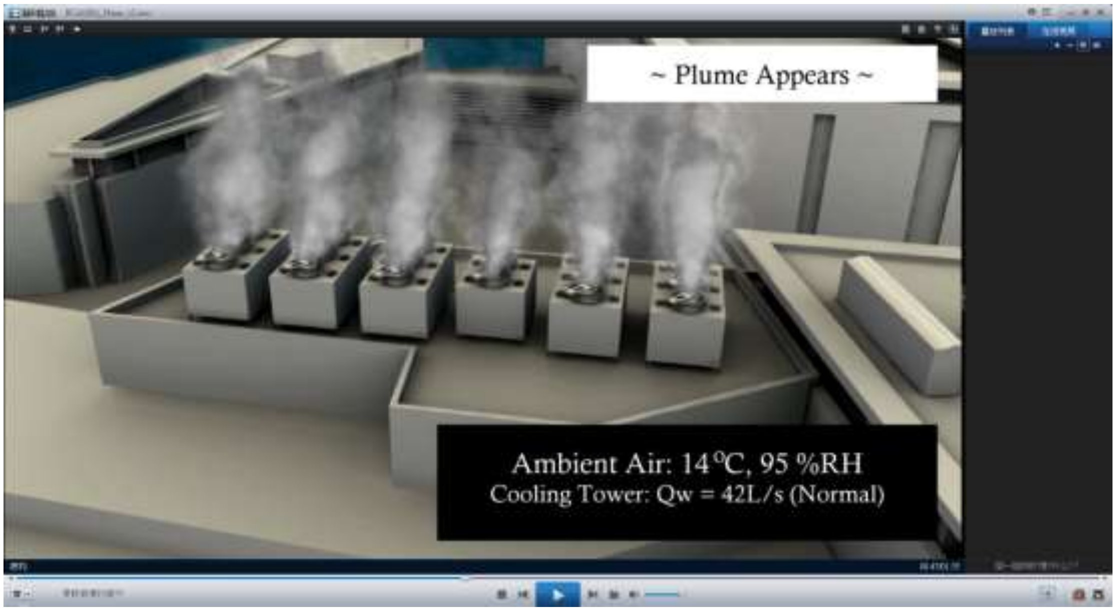


Figure 115 Transient graphical results of flow pattern of cooling tower discharge

Figure 116 Transient graphical results of flow pattern of cooling tower discharge with no visible plume

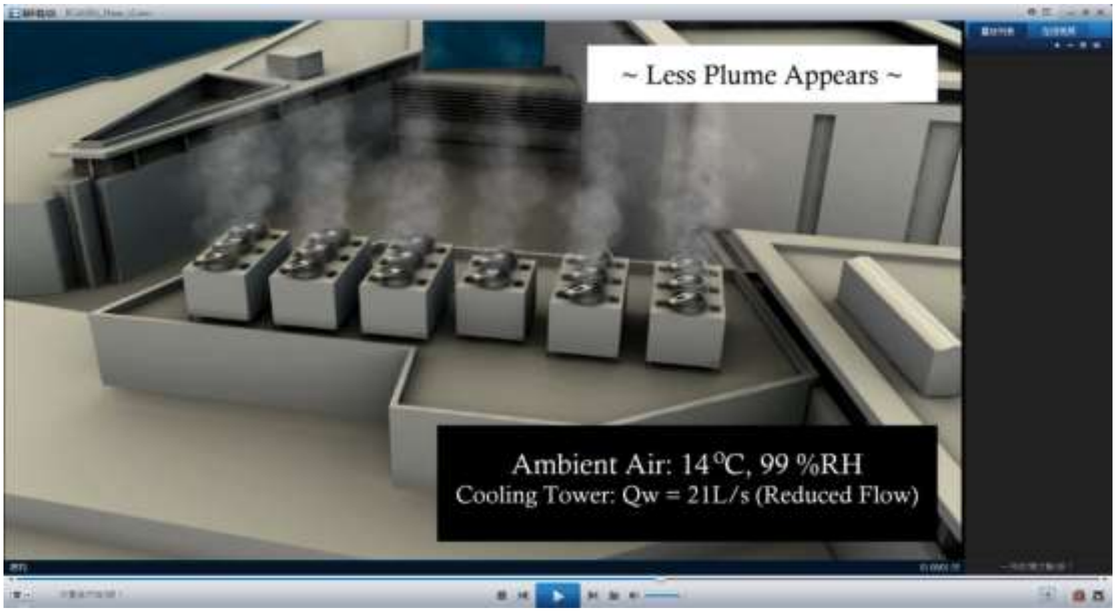


Figure 117 Transient graphical results of flow pattern of cooling tower discharge with less visible plume

8.2 Conclusions

The web-platform for cooling tower is a comprehensive tool that compiles many related topics of cooling tower into a single and user-friendly website to allow for easy finding by those who has to manage cooling tower on a daily-basis, as well as increases the awareness of the society with the use of cooling tower, especially on the potential risk of spread of Legionella via cooling tower.

The use of this web-platform can also bridge the gap between the industry and the research progress that are recently developed. For example, the use of the Poppe Approach that is more accurate than the Merkel Approach. The Merkel Approach is widely used in the cooling tower industries because the mathematical theory is easier to write in scripts compared to the Poppe Approach. However, based on the studies carried out in the current study, the more sophisticated but more accurate Poppe Approach is incorporated into the web-platform to provide a more accurate heat rejection and visible plume evaluation for parties of interest.

Apart from the incorporation of the more sophisticated model in the web-platform, it also provides several functions that cooling tower operators will find valuable, such as the Code of Practice for cooling tower that monitors the safety and performance of the equipment throughout its service life, the dispersion rate of cooling tower in an urban environment, and detailed information of different aspect related to cooling towers.

The web-platform is designed to be very user-friendly, and aims to allow user to find information of interest instantly. As a result to enhance knowledge sharing between researchers (academy) and facility management staff (industry) on cooling towers and bridge the 20 years gap between the two parties in order to provide a better management plan for cooling towers, and thus enhance the sustainability level of cooling tower from design to operating and maintenance stages.

Chapter 9 – Conclusions

The purpose of this chapter is to conclude the process to investigate an approach to reduce / eliminate the frequency of visible plume. The use of the water shedding approach will show promising result on reducing the severity of visible plume, and with the use of CFD simulation can show the reduction of severity of cooling tower visible plume.

The following shows the progress and findings of each chapter of the thesis.

9.1 Model Validation with Full Scale Test

At present, the Merkel Approach is widely adopted in the industry as it is easy to use; however, this specific calculation approach is not as accurate when calculating the discharge air condition compared to Poppe Approach. In view of this, the more sophisticated model, the Poppe Approach, is comparatively more accurate when calculating the discharge air condition. This model has been validated for natural draft cooling tower, yet it has not been validated on mechanical cooling tower, which is more suitable for use in Hong Kong for buildings due to the compactness in nature. With this in mind, validation of the Poppe Approach is carried out on a full scale mechanical cooling tower. A careful experiment is carried out, and high quality measurement tools are used to measure the water and air condition at inlet and discharge point. The measured discharge air condition is used to compare with the calculated discharge air condition based on both the Poppe Approach and the Merkel Approach. The results show that the Poppe Approach is accurate when compared to the measured results, and is more accurate than the discharge air condition calculated by the Merkel Approach.

9.2 Experimental Test & CFD Simulations & Comparison

In order to understand the visible plume behavior in an urban environment, CFD simulations is one of the most appropriate tool to be used as it is more cost effective and less time consuming. However, many CFD simulations are available in the industry, and study is required to ensure the accuracy of the simulation model. With this in mind, a testing chamber is designed to create an artificial environment for visible plume to validate the CFD simulation, as well as the cooling tower plume formation. This validation process is not only meaningful in validating CFD simulation approach, but also a great leap for cooling tower research because of the controllable ‘thermal load’ and ‘environmental’ conditions.

When comparing CFD simulation with the experimental results, it is found that the CFD simulation results match with the flow pattern of the visible plume by comparing the temperature readings at the same spot within the testing chamber with the 3D domain of the CFD simulation.

9.3 Visible Plume Abatement with the Use of Water Shedding Approach

Hong Kong is an urban city with a subtropical climatic condition, where visible plume is very common when the moist air discharges from cooling towers mixes with humid ambient air. Visible plume is not recommended in Hong Kong as it can cause disturbance to both building occupants and pedestrian with respect to aesthetic issue, misunderstanding it as smoke and condensation on building equipment that can cause corrosion. Many researches have focused on visible plume abatement, which include the use of heat coil to generate hot and dry air with moist air within a cooling tower. Yet, this theory have several disadvantages including increasing in pressure drop in cooling towers that reduces performance of cooling tower and sometimes difficult to provide addition energy for these heat coils. In this study, the water shedding approach is proposed as one of the visible plume abatement approaches.

The principle of the water shedding approach is that when visible plume occurs, and if there is additional cooling tower not in use, then water flow rate can be split between two or more cooling towers, or even by-pass portion of the water within the plant. This will allow visible plume to be reduced or even eliminated while at the same time meeting the heat rejection requirement.

In this study, a scenario is set up to test the performance of water shedding approach within a cooling tower plant that consists of five cells with three cooling towers and one smaller cell that consists of two cooling towers. In the analysis, it is shown that there are 1,047 hours, which is 12% of a year, that there is a high potential for visible plume to occur. In addition, visible plume is found to occur more frequent in March, in which there will be a total of 214 hours of visible plume occurrence. By adopting the water shedding approach, the frequency of visible plume can reduce from 1,047 hours to 647 hours (38% reduction), and the severity of visible plume is reduced by 40 ~ 60%.

The water shedding approach does not share the disadvantage of the cooling tower with air heating application, as there is no need in modifying the cooling tower nor the cooling tower plant. Another advantage that the water shedding approach has over the cooling tower with heating application is that the effect is almost instantaneous.

9.4 Dispersion of Cooling Tower Plume in Urban City

With the understanding of the heat transfer model of cooling tower that leads to discharge air condition and CFD validation on the cooling tower visible plume formation with experimental test, the next step is to use the validated CFD technique to identify the potential issues of visible plume within an urban environment. This is of particular importance in urban city where cooling tower has high tendency in creating aesthetic issue (sensation and practical), maintenance of issues during operation and spread of disease with contaminated drifts to its immediate surroundings.

Generic model is constructed to identify the visible plume dispersion within an urban environment with the use of 3D model. Furthermore, comparison has also been made to identify the reduction in visible plume dispersion and its effect after adopting water shedding approach to reduce the moist level of discharge air.

From the results, it is found that although the water shedding approach can reduce visible plume severity, it is not be able to completely eliminate the visibility of plume. By reducing the visible plume, the chance of spreading Legionnaires' Disease can be reduced due to less chance of condensation of the "polluted" water that is discharged from the cooling tower into the environment. As discharge of cooling tower cannot be completely eliminated at all times (especially during spring with high RH in ambient air), it is not recommended to place cooling towers within zones that shows similar configuration as a wind canyon. Instead, cooling tower should be placed at roof level of buildings in order to reduce the impact of visible plume to its immediate surroundings.

9.5 Development of the Web-based Cooling Tower Platform

The development of the web-platform of cooling tower is to bridge the gap between the academic and the industry, as it is seldom that the research findings are implemented into the industry. This in turns lowers the effect of the most sustainable and most advanced technology to be used in the society. However, by developing a user-friendly web-platform, it is possible to pass these new ideas into the industry with ease, and to provide solutions to many of the existing questions that can be answered with the current level of researched techniques.

For example, the comprehensive research on plume abatement protocol is developed based on the most sophisticated model. However, as the mathematical model is quite complicated and involve iterations, manufacturer or engineers usually prefer the use of the less complicated and less time-consuming Merkel Approach.

With the development of this web-platform for cooling tower, anyone can carry out cooling tower design with a more accurate mathematical model as well as to optimize the design with visible plume abatement.

Beside this sophisticated model, the web-platform also consists of other valuable information that allows society to have a better understanding on cooling tower and related operating health issues (such as Legionnaires' Disease) . In addition, the web-platform can also provide a checklist for cooling tower that aligns with local guidelines.

9.6 Concluded Statement

This section summarizes the conclusions and to responses to the objectives presented in Section 1.6

- Objective 1 – Heat Transfer Mechanism of the Cooling Tower in order to calculate more accurate visible plume condition
- Objective 2 – Full Scale Tests in order to validate the sophisticated Poppe Approach with a real mechanical cross-flow cooling tower
- Objective 3 – Environmental Chamber Study of Wet Plume of Cooling Towers in order to understand the real visible plume flow pattern and validate with Computational Fluid Dynamics (CFD) Simulations
- Objective 4 – Visible Plume Abatement for Cooling Towers in order to find an alternative approach to carry out visible plume abatement
- Objective 5 – Dispersion Analysis of the Cooling Tower Plume in order to understand how visible plume affect an urban city with the use of CFD Simulations
- Objective 6 – A Computer Aided Cooling Tower Manager to help the public to understand the risk of visible plume within an urban environment

The following shows each response to each individual objective as shown above:

- Response 1 – The more accurate Poppe Approach is adopted to calculate a more accurately the discharge condition of a mechanical cooling tower and is used to compare with the industrial approach (refer to Objective 2)
- Response 2 – The real size cooling tower is adopted with a laboratory facility and validated the Poppe Approach and also showing that the Poppe Approach is more accurate than the industrial approach.
- Response 3 – An environmental chamber is designed to review the shape of the plume and validated the CFD codes for further analysis showing in response to Objective 5.
- Response 4 – An alternative approach, the water shedding approach, is developed in order to reduce the occurrence of plume. In the evaluation, it is shown that the occurrence of plume hour can be reduced by 38%.
- Response 5 –Study has shown that as cooling tower is located within an urban canyon, water shedding approach can reduce the RH of cooling tower discharge and reduces the severity of visible plume distribution within the urban environment.
- Response 6 – The knowledge-based web platform is displayed. The platform demonstrates that consists of valuable information related to cooling tower that can increase the public awareness

towards cooling tower.

9.7 Overall Conclusions

Visible plume was considered as a nuisance to the public due to health and visual issue especially in urban cities. The typical approach to abatement visible plume is by installation of heating coils to reduce relative humidity of air, but this approach was difficult to apply in Hong Kong due to difficult in finding the heat sources in a city located in subtropical region, thus an alternative approach was required.

Prior to develop the alternative approach, an accurate discharge air condition calculation would be required. The Poppe Approach was adopted and validation was carried out with a real size cooling tower located in a manufacturing plant in China. Furthermore, formation of the visible plume was also studied to understand the plume flow pattern under different climatic condition. With this reason, an artificial environmental chamber was designed with the use of the Poppe Approach calculation and tests were conducted. CFD simulation was also carried out and validated with the experimental results.

By using the Poppe Approach, a new visible plume abatement approach, the water shedding approach, was developed. The water shedding approach was designed and capable to calculate the reduction in visible plume frequency and severity. A visible plume abatement evaluation was carried out based on the building load of a commercial building with the use of the developed water shedding approach. By using the Hong Kong climatic data, the evaluation showed the new visible plume abatement approach could reduce the frequency of visible plume abatement by 38.2% and severity of visible plume was reduced by 40 – 60%.

Combining the CFD simulation and the water shedding approach, evaluation was conducted to identify the effectiveness of water shedding approach. The result showed that the developed water shedding approach could reduce the maximum temperature within an urban environment by 0.33 ^{o}C and maximum moisture content of 0.0003 kgDA/kgM.

In order to bridge the gap between academic and industry, a web-based platform was created that stored information related to cooling tower, as well as the fast calculators (the Poppe Approach calculator and the visible plume abatement calculator) developed during this research topic. This web-based platform would provide engineer a user friendly tool to carry out evaluation in cooling tower plant design and visible plume abatement evaluation.

9.8 Future Work

With future work, more study will be carried out on incorporating the water shedding approach in a building to carry out case study with the operating and maintenance team to develop a control strategy on plume abatement. These research and case study should be recorded and incorporated into the currently developing new cooling tower web platform once ready to enhance knowledge sharing on cooling tower control strategies to reduce the health and visual impacts of visible plume.

It is also for future work to conduct measurement work for cases with and without water shedding approach, to measure the discharge air condition at several locations near the tower, such as above discharge jet and area near location. Temperature and relative humidity sensors are highly recommended during measurement for both cases of with and without water shedding approach, then the reduction in visible plume severity based on measurement results can be identified. It is then possible to compare the reduction in visible plume between the measurement results and the calculated results (POP Index as proposed in Chapter 6) to verified the POP Index calculation.

9.8.1 Visible Plume Abatement with the Use of Water Shedding Approach

In the study, a theoretical model of the water shedding approach is used in order to identify the optimized capability of a cooling tower plant to operate in mode that could fulfill the cooling capacity of the plant while reducing or even to the extent of full elimination of visible plume at certain period of time during the year. However, the practicability of the model would still be required in order to have the cooling tower plant able to operate as discussed. This would involve combining of chiller system with the cooling tower system, to show that with the operating mode of the cooling tower system, there is no adverse impact on the entire system itself that requires to deliver the intent design cooling capacity to remove the heat generated in buildings during normal operation.

Secondly, the theoretical water shedding approach would still need to be further enhanced by having a greater understanding on how cooling tower operates. For example, whether or not the cooling tower could operate at such low load, such as the fan speed of cooling tower could not be lower than 50% and that the water distribution along the fill could not be lower than a certain amount to ensure the water droplets are very fine thus allow for large total surface area of contact between water and air within the fill during the cooling process.

9.8.2 Dispersion of Cooling Tower Plume in Urban City

Although a generic study has been carried out to identify the impact of cooling tower plume within an urban city, yet the case does not often occur except in areas where cooling tower is constructed more than a decade ago. As more and more cooling towers emerge within an urban city such as Hong Kong, towers are more likely to be placed at the roof of a building. Therefore, future study should focus on whether or not the visible plume would flow towards the outdoor air intake point of all building within close proximity to the cooling tower plant. This would further enhance the value of the visible plume dispersion study in urban city as that would allow building users to know whether or not the plant is designed at a location with the least health risk and whether or not it would affect the HVAC system within close proximity of the plant.

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