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On the Performance Evaluation of Microtextured Surfaces Using Computational Fluid Dynamics: A Comparative Study

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Abstract

Microtextured surfaces are gaining rapid uptake in industrial sectors for bespoke functional applications that require specific tribological, mechanical and biological properties, such as friction and wear, corrosion resistance, wettability, bio-reactivity and so on. Although comprehensive study has been undertaken to create optimal texture designs that adapt to each respective application, the design process still requires elements of trial-and-error approaches. In order to minimise the uncertainty of the trial-and-error design process, this study centres on employing computational fluid dynamics (CFD) software tools to assess isothermal fluid flow velocity profiles on the microtextured surfaces, in relation to the energy-sector applications. A comparative analysis has been undertaken on the effectiveness of three different CFD tools to predict the velocity profiles generated on the textured surfaces under atmospheric fluid flow conditions (1000 L/min) with a fixed input air velocity (3.78 m/s) at room temperature. The results from the CFD analysis were then compared with that obtained from an experimental set-up involving a scallop-shaped textured surface produced via micro-wire electro discharge machining. The data suggest that the predicted velocity profile on using the scan of a real manufactured surface is significantly closer rather than when using a CAD idealised textured surface. However, there remains some limitations with the meshing that require further research.

Keywords: Microtextured Surfaces, Computational Fluid Dynamics, Biomimetics.

1. Introduction

1.1. Microtextured surfaces in the energy sector

The demand for the reduction of energy consumption in large-scale industrial sectors has never been so paramount as it is today under the recent 'climate emergency' scenario. Despite the increasing urgency of moving to the renewable energy sources their contributions to the global energy demand have only moderately increased by ~2.5% over the past decade [1]. New investment in the fossil fuels also creates hinderance to increase the proportion of energy usage from the renewable resources. Consequently, futuristic alternative high energy sources, such as gales, hurricanes, floods and other highly energetic meteorological phenomena, could be added to the pool of renewable resources to reduce the fossil fuel consumption. The current project aims at developing new technologies for high peak, perishable energy (HPPE) recovery, to enhance thermal and energy production processes. Certain objectives of HPPE recovery are the reduction of boundary layer thickness (and drag force) of isothermal diffusion turbulent fluid flow and the enhancement of condensation heat transfer in a cost-effective way. Here, microtextured surfaces play a crucial role in topographical modification via a passive mechanism. Typical examples include their usage for heat exchangers, heat extractors, and thermal control units in power plants during cooling and boiling [2].

With regard to the condensation phenomenon microtextured surfaces exhibit noticeable effects on the heat transfer by transferring energy from the large latent heat, associated with matter's phase change [3]. On a heat exchanger in energy systems, the heat is passed onto the textured surfaces, rather than to the drier air. Additionally, microtextured surfaces can also reduce blow-off and flashback phenomena in combustion systems [4,5,6].

Numerical analysis and experimental trials have shown that biomimetic microtextured surfaces can provide a reliable passive drag reduction mechanism, coupled with useful hydrophobic or hydrophilic properties [7,8]. Over the past decade, significant progress has been made on the design and fabrication of surface textures, leading to vast applications of biomimetic microtextures. Nonetheless, the creation of optimal texture designs for specific surface properties still requires significant elements of expensive trial-and-error approaches. Therefore, it is imperative to undertake reliable numerical approaches to attain the optimal texture design parameters that could render the best targeted outputs. This paper focuses on employing Computational Fluid Dynamics (CFD) techniques to predict the velocity profiles generated on microtextured surfaces under atmospheric fluid flow conditions. The results are then compared with experimentally measured fluid velocities on a scallop-textured surface.

1.2. CFD software

The opportunity of CFD lies on the capacity to extract data at a limited number of locations in the system. CFD provides the ability to theoretically simulate any physical condition. With ever increasing computational power, CFD techniques have become effective tools for the prediction of fluid-flow phenomena, as they can efficiently solve the Navier-Stokes equations [9]. The continuity, momentum and energy equations are the three fundamental conservation laws that comprise the Navier-Stokes equations as follows:

Continuity equation: $\frac{D\rho}{Dt} + \rho \frac{\partial U_i}{\partial xi} = 0$ (1)

Momentum equation:

$$\rho \frac{\partial U_j}{\partial t} + \rho U \frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_i} + pg_j \qquad (2)$$

where, $$\tau_{ij} = -\mu\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_J}\right) + \frac{2}{3}\delta_{ij}\mu\frac{\partial U_k}{\partial x_k} \qquad (3)$$

Energy equation:

$$\rho c_\mu \frac{\partial T}{\partial t} + \rho c_\mu U_i \frac{\partial T}{\partial x_i} = -P\frac{\partial U_i}{\partial x_i} + \lambda\frac{\partial^2 T}{\partial x_i^2} - \tau_{ij}\frac{\partial U_j}{\partial x_j} \qquad (4)$$

These equations, along with the conservation of energy equation, form a set of coupled, non-linear partial differential equations. For most engineering problems, it is not possible to solve these equations analytically, hence the use of CFD approach is essential. However, for a computer to be able to solve these equations, it needs to transform them into discretised forms. The transformation can be done with translators which are numerical discretisation methods, such as finite difference, finite element, and finite volume methods whose performances rely significantly on the meshing process [10]. The meshing process becomes even more challenging when the scale is reduced to the micron level. Not all CFD software can handle the required mesh refinements and as the number of cells increases the need for higher computing power also escalates. This brings uncertainties in the predictive performance of such approaches at microscale. Thus, a balance between the refinement and cell sizes is needed to achieve the results that converge into a viable solution.

A few CFD simulations conducted at microscale have been reported, such as for the study of patterned surfaces used in hydrodynamic lubrication [11], for the performance evaluation of a microvortex generator on aerofoil and vertical axis turbine [12] and for the modelling of ultra-high rotational speed micro-friction stir welding [13]. As a result, the scope of the present study is to explore the different software tools' capabilities, such as, their programming language, meshing precision, solutions methods, precision on the solution method, time needed to simulate, accuracy to simulate real textures at micron-scale and the time required to analyse it.

1.3. Aim and objectives

The aim of this study is to explore which CFD software is the most promising for accurately and effectively evaluating the performances of microtextured surfaces. This forms a part of the final aim of the current project - to implement novel design optimisation algorithms that could help determining the best shapes and dimensions to apply to various biomimetic texture designs.

2. Methodology

2.1. Microtexture design selection

Previously, Martinez-Zavala et al. [2] tested a small range of biomimetic texture designs (diamond, sharkskin, lotus and scallop), manufactured via micro-wire electro discharge machining (µ-WEDM) and laser ablation, for boundary layer thickness determination under isothermal turbulent fluid flow conditions. The results were compared with the predicted values obtained via Hydro3D software (developed at Cardiff University [14]).

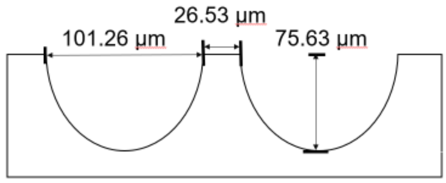

Fig. 1. A schematic of the scallop design (in microns).

However, Hydro3D is limited for optimisation techniques as it is primarily used for environmental fluid dynamics. Therefore, the solver models and methods are still being developed as their community expands. Consequently, other software tools are investigated in this study with a wider range of models that could potentially merge with machine learning optimisation algorithms. In [2], the most adequate texture for an initial design optimisation appeared to be the scallop design. The same design is also used in this study, as its main design variations can be fully defined using three parameters only, viz, scallop width, scallop depth and riblet width (Fig. 1), thus ensuring the design to generate easily.

2.2. Experimental set-up

The scallop design was manufactured via µ-WEDM on the surface of a Ø25mm insert. A 3D optical scan of the resulting texture is shown in Fig. 2(a). In average, the width of the grooves was measured to be 101.56 µm, the gap between each groove (riblet width) was 26.53 µm and the groove depth was 75.63 µm.

Following this, experimental measurement of isothermal fluid velocities was carried out in an air duct flow rig, designed to test different microtextures at different angles with respect to the flow direction. The rig comprised of a centrifugal fan, a fluid straightener, duct test discs, a unislide and a hot-wire anemometer. More details about the experimental rig are presented in the study by Al-Fahham [14]. The centrifugal fan delivered air at a flow rate of 1000 L/min with an input velocity of 3.78 m/s. The microtextured specimen was then placed onto the disc in inverted position with the textured surface inside the duct (see Fig. 2(b)). A hotwire anemometer was employed to record the air velocities at a lateral distance of 5000 µm from the specimen. Measurements were taken at every 100 µm in the vertical direction from the textured surface until the distance reached 1 mm. Further measurements were taken at every 1 mm until the distance reached 13 mm from the surface to ensure that the velocity profiles included the entire boundary layer.

2.3. Simulation set-up

For the simulation evaluation, two commercial CFD software tools were selected due to license availability, namely STAR-CCM+ (CD-adapco 2020) and ANSYS Fluent (ANSYS 2022). The third software selected was OpenFOAM® v2106.

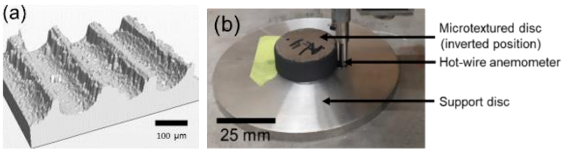

Fig. 2. (a) 3D scanned image of a real textured surface, (b) experimental set-up for the air velocity measurements.

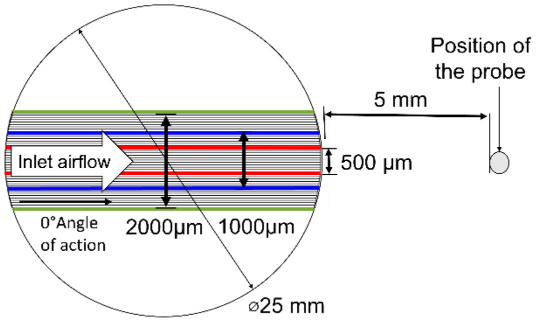

Fig. 3. Complete insert with simulated width segments.

It is an open-source software that could potentially enhance an opportunity for complex optimisation development as it is fully scriptable and could be fully automated. All the simulations presented in this paper were performed on a computer with I7 core and 8 GB RAM memory with two computer processors.

The scallop design shown in Fig. 2(a) was selected for the simulation, using the same texture dimensions as shown in Fig. 1. However, only central segments of the textured circular area used in the real experimental set-up were considered to run the fluid flow simulation, to try to reduce the computational time (see Fig. 3), because the simulation of the complete surface failed with all software. The height of the textures was 76 µm and three central segments width were tested (500 µm, 1mm & 2mm), to explore the effects of the simulated area on the accuracy of the model prediction. Similarly to the experimental set-up, the outlet fluid velocities were calculated at a lateral distance of 5 mm from the textured surface, parallel to the input air flow direction and at a 0° angle of action with reference to the scallop grooves.

2.3.1. Simulation parameters

For all simulation, the K-Epsilon model was used, and the geometry of the surface texture was imported via one single .step file, as a cavity for the fluid domain. The smallest mesh size that ANSYS and STAR-CCM+ could process, when creating a mesh with the scallop design provided, was 10 µm, using symmetry properties and inflated layers in the prism layer (which also saved computer resources), and was therefore used for all simulations. The main difference between the three simulations software is that they use different solvers. ANSYS used a *pressure based segregated, second order upwind turbulent dissipation rate* solver, OpenFoam a *ICOFoam as a simple flow* solver. STAR-CCM+ used *segregated isothermal fluid solver.*

3. Results and discussion

The use of different segment widths was only tested on ANSYS and the results are shown in Fig. 4. The 2mm width achieved the best results with a 5% deviation from the experimental results. Therefore, in this investigation all other simulations were also done with the 2mm width. But, further investigations should be conducted to identify an efficient segment width that may increase the simulation accuracy.

A representative screenshot of the simulated fluid flow is shown in Fig. 5 and Fig. 6 shows the results of the isothermal fluid flow velocity profiles predicted using the three CFD software when testing CAD textured surfaces.

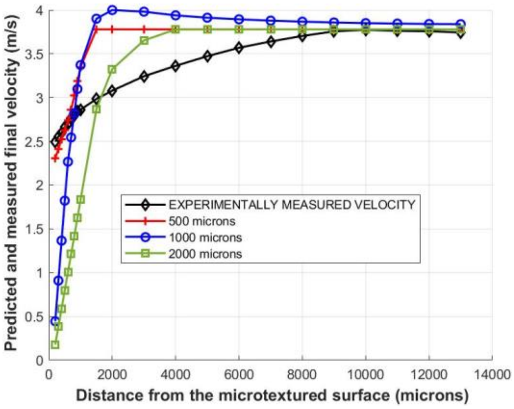

Fig. 4. Results with different segment width using Ansys.

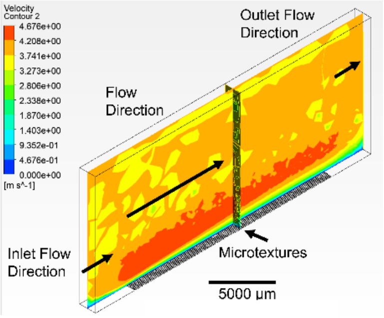

Fig. 5. Screenshot of the simulated fluid flow using ANSYS.

When testing CAD surfaces, the time taken for the simulation in ANSYS, STAR-CCM+ and OpenFOAM was 48mn, 52mn and 72mn respectively. It should be noted that this time does not include the setting up of boundaries conditions, meshing and physics, which took more than 1.5 hour for each simulation.

In order to evaluate if the use of CAD/idealised textures (Fig. 1) is sufficient, the simulation was conducted using the scan of a real textured surface (in a cloud-of-point format) produced by WEDM (Fig. 2). In this investigation, due to technical issue with the surface file format, only ANSYS was used. The velocity results are also presented in Fig. 6.

The three software produced similar profiles, albeit with some offset from the experimental data. Overall, when comparing the predicted fluid velocities with the measured velocities. ANSYS using the scan of a real surface overestimated the velocities by 16.29% on average, while using a CAD texture OpenFOAM, ANSYS and STAR-CCM+ overestimated the velocities by 20.61%, 24.60% and 25.11% respectively.

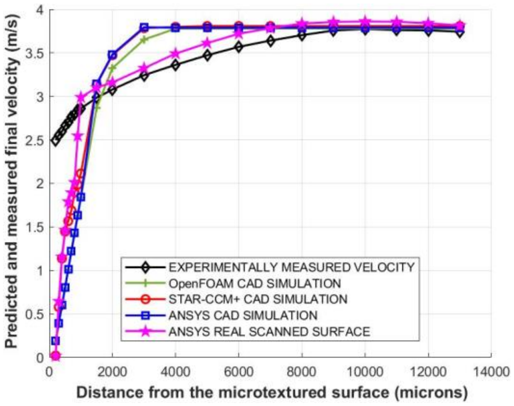

Fig. 6. Fluid velocities (2mm textured segment width)

Also overall, the velocity predictions appear to be relatively accurate above 0.2 mm from the textured surface, but this is clearly not the case when the distance is <0.1 mm. This may suggest meshing issues at microscale, as the meshing was limited to 10 µm cell sizes, and this highlights constrains in the current off-the-shelf simulation solutions. This issue will therefore be investigated further.

Looking at the results in more details, Fig. 7 shows the % deviations of the predicted fluid velocities from the experimental velocities. ANSYS using the scan of a real surface is in average 5% different, while using a CAD texture, OpenFOAM, ANSYS and STAR-CCM+ are 10%, 16% and 17% respectively.

This confirms that ANSYS using the scan of a real surface gave the closest prediction results. Thus, further work should be conducted to evaluate the results of STAR-CMM+ and OpenFOAM with the same surface.

Anyhow, this suggests that the use of an “idealized” CAD design when simulating the behaviour of a microtextured surface might not be sufficient and that manufacturing inaccuracies, limitations (e.g., surface roughness, rounded edges) or related surface defects at microscales have nonnegligible effects on the simulation prediction accuracy. However, the computing time required for the simulation that used the scan of a real surface was significantly greater than when using a simplified CAD version of the texture design. A balance between them should be considered to achieve accurate results efficiently. To evaluate this the testing of further texture designs needs to be conducted, in particular considering finer meshes.

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4. Conclusions

The study indicates that all three CFD tools (commercial software STAR-CCM+ and ANSYS Fluent, and the open-source OpenFOAM) have the potential to relatively accurately simulate flow behaviour on top of a microtextured surface and to be used for microtextures optimisation. And OpenFOAM appears to be the best candidate due to its fully open programming library and to the good results obtained when using a simplified CAD texture design.

Also, in this study, the use of the scan of a real manufactured texture, rather than a simplified CAD texture design, appeared to bring non-negligible improvements in the prediction accuracy.

However, due to file format and related meshing issues, only ANSYS could be used to run a simulation with such scan. Thus, further investigation to test real scans of manufactured surfaces with all software will be conducted. Finally, the study was conducted on a single texture design produced by WEDM. Further study will evaluate a wider range of texture designs produced using other manufacturing technologies.

Ultimately, the key will be to find optimum conditions that provide accurate enough predictions at low enough computational costs, and this will be a trade-off between the complexity of the texture design used (how close it is to a real manufactured surface), the area size of the simulated texture and the meshing process.

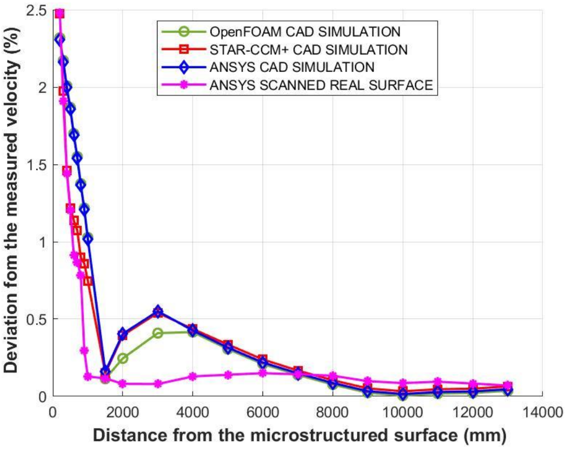

Fig. 7. Deviation of the predicted fluid velocities from the experimentally measured data (2mm segment width)

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