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# Heat Transfer Enhancement On A Flat Plate Using Oriented Semi-Circular Grooves: Numerical And Experimental Study

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**ABSTRACT**

Three panels were fabricated from Duralumin with dimensions of (400 × 300 mm). The first was a reference (flat plate), the second had transverse grooves perpendicular to the flow direction, and the third had longitudinal grooves parallel to the flow direction. The experiments were conducted in an open wind tunnel with a fixed flow velocity of 8 m/s. The ANSYS Fluent 2020 environment was used for numerical simulations, and the k-ω SST turbulence model was used to analyze the flow physics within the grooved regions.

The results indicate that both grooved designs significantly improve the heat transfer coefficient (h) compared to a smooth surface. The transverse design demonstrated superior thermal performance, attributed to the periodic separation and reattachment of the flow, which hinders the formation of the thermal boundary layer. In contrast, the longitudinal grooves enhanced secondary flow vortices that improved mixing while reducing pressure drop. Validation of the numerical model using experimental data showed excellent agreement, with a maximum deviation of less than 8–12%.

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## I. INTRODUCTION

Modifying surfaces or adding certain shapes (vortex generators), for example, are passive ways to improve heat transfer and energy efficiency. They are reliable solutions that do not require external power sources, which significantly reduces operating costs and extends the life of the system, as they lead to increased turbulence and improved heat transfer coefficient (1).

Enhancing convective heat transfer on flat panels is important in the thermal engineering of devices such as heat exchangers, electronic cooling systems, solar collectors, and aerodynamic heating applications. One passive technique for improving heat transfer involves modifying the surface using grooves. This method affects the boundary layer, flow separation, and eddy current formation.

An experimental study was conducted to investigate the effect of the distance between prominent semicircular ribs. The result was an improvement in thermal performance, accompanied by an increase in pressure drop. (2).

This study examined the effect of ribs and perforated ribs on heat transfer in square channels. The perforated polygonal channel has consistently outperformed the polygonal channel due to increased surface area and turbulence. (3)

Among the various groove shapes, semicircular grooves offer advantages, including lower pressure losses than sharp-edged grooves. However, the orientation of these grooves relative to the flow direction plays a crucial role in optimizing heat transfer and flow resistance. A limited number of systematic studies have directly compared the effects of groove orientation using a combination of experimental and numerical approaches.

Changing the groove orientation significantly alters the local flow topology, with certain angular orientations favoring the formation of longitudinal vortices that disrupt the thermal boundary layer more effectively than the transverse configurations. To address this gap, the present study examined the thermal and hydrodynamic performance of a flat plate featuring semi-circular grooves arranged in orientations both perpendicular and parallel to the airflow.

**2. Experimental Setup**

**2.1. Geometric Configuration:**

The effectiveness of the flat plate in heat transfer was studied by manufacturing three aluminum plates. The geometry of this study is shown in **Figure 1.**

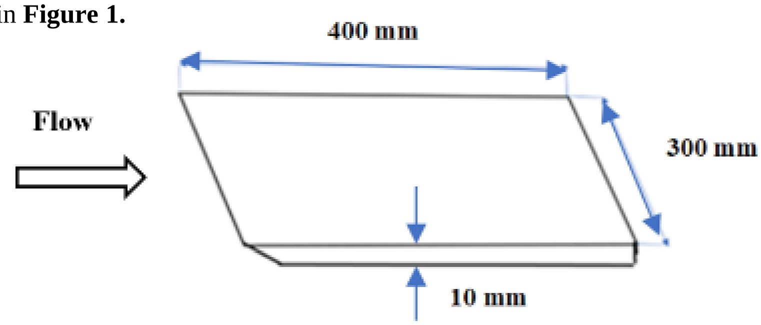


**Figure 1.** The flat plate used in the experiment

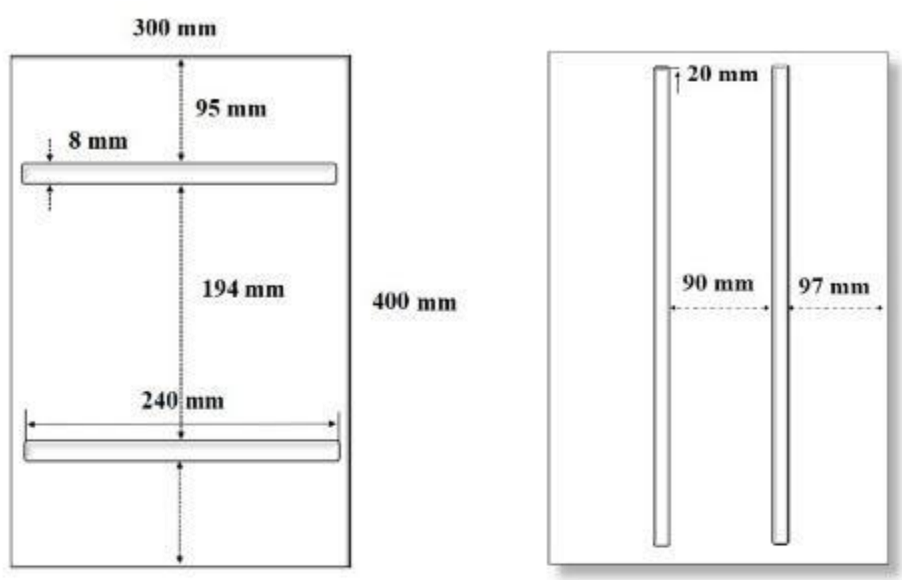


**Figure 2.** Dimensions and location of grooves on the flat panel.

At Dijlah University, a low-speed wind tunnel was manufactured, as shown in **Figure (3),** and the thermal efficiency of the flat panel was calculated using it. The air speed was fixed at (8 m/s).


**Figure 3.** Photographs of experimental set up.

Nine thermocouples were mounted on each panel. Four electric heaters are also installed as a heat source. The flat panel is placed horizontally in the center of the wind tunnel test section (30*30*40 cm). When the heat source is switched on, the temperatures of all the heat transmitters are measured. When the temperature reaches 80 degrees, the wind tunnel fan is switched on, and the air speed is monitored until it reaches 8 m/s. The clock is then started, and the temperatures are read every minute.

**2.2 Numerical Method and Validation**

To achieve the required numerical analysis, the ANSYS 2020 R2 environment was employed as a software tool specializing in computational fluid dynamics, in order to simulate flow patterns and heat transfer over the plate. In the present study, the assessment of the thermophysical characteristics of air and aluminum at a temperature of 20 °C was employed, as delineated in **Table 1.**

Table 1 Thermophysical characteristics of air and aluminum at a temperature of 20°C.

| Thermal properties | Air | Aluminum |
|---|---|---|
| $\rho$ (kg/m$^3$) | 1.2 | 2712 |
| $C_p$ (J/kg K) | 1007 | 871 |
| $k$ (W/m K) | 0.02498 | 202 |
| $\mu$ (kg/m s) | 1.88E−05 | ---- |

**2.2.1 turbulent airflow model (Governing equations)**

**Continuity Equation (Mass Conservation)**

The conservation of mass for an unsteady compressible flow is expressed as:

$$\partial\rho/\partial t + \nabla\cdot(\rho V) = 0 \quad (1)$$

For incompressible flow, the equation reduces to:

$\nabla \cdot V = 0$

**II. Momentum Equation (Navier–Stokes Equations)**

The conservation of momentum for transient turbulent flow is given by:

$\partial(\rho V)/\partial t + \nabla\cdot(\rho VV) = -\nabla p + \nabla\cdot\tau + \rho g + F$ ..................................(2)

The viscous stress tensor is expressed as:

$\tau = \mu\, [\nabla V + (\nabla V)^T] - (2/3)\, \mu\, (\nabla\cdot V)\, I$

**III. Energy Equation (Unsteady Heat Transfer)**

The general form of the transient energy equation is:

$\partial(\rho E)/\partial t + \nabla\cdot [V (\rho E + p)] = \nabla\cdot (k_{eff} \nabla T - \Sigma\, h_j J_j + \tau_{eff} \cdot V) + S_h$ .......(3)

**IV. Turbulence Modeling: k–ω SST Model**

The Shear Stress Transport (SST) model combines the advantages of the k–ω model near walls and the k–ε model in the free stream.

**- Turbulent Kinetic Energy Equation**

$\partial(\rho k)/\partial t + \nabla\cdot(\rho k V) = \nabla\cdot [(\mu + \mu_t/\sigma_k) \nabla k] + P_k - \beta^* \rho k \omega$ ..................(4)

**- Specific Dissipation Rate Equation**

$\partial(\rho\omega)/\partial t + \nabla\cdot(\rho\omega V) = \nabla\cdot [(\mu + \mu_t/\sigma_\omega) \nabla\omega] + \alpha\, (\omega/k)\, P_k - \beta\rho_\omega^2 + D_\omega$ .(5)

**V. 5. Turbulent Viscosity**

The turbulent viscosity in the SST model is defined as:

$\mu_t = \rho k / \omega \times 1 / \max(1, (a_{\iota\omega})/(SF_2))$ …………………...…………..... (6)

**VI. Effective Thermal Conductivity**

$k_{eff} = k + (c_p \, . \, \mu_t) / Pr_t$ ..........................................................................(7)

**VII. Production of Turbulent Kinetic Energy**

$P_k = \mu_t \, . \, S^2$ ...............................................................................................(8)

Where:

$S = \sqrt{2 s_{ij} s_{ij}}$

and $s_{ij}$ is the strain rate tensor.

**2.3 Grid-independent test**

Evaluating the generation of networks within simulation frameworks constitutes a critical component of computational fluid dynamics analysis. The comprehensive physical domain is encompassed by the network, which serves as a meticulous lattice-like geometric configuration. Networks facilitate the computation of discrete volumes necessary for the application of conservation principles. The preliminary phase entailed the calculation of numerical solution equations that characterize the mechanism of physical network formation. The efficacy of the solution is contingent upon the integrity of the network. An optimal network can be achieved through enhancements in solution quality; conversely, the employment of a poorly developed network results in discrepancies from the numerical solution. A tetrahedral block was employed to construct the three-dimensional network, as illustrated in Figure 2. Samples of varying dimensions (network density) were evaluated to ascertain the appropriate network density for both flat and perforated plates. For the flat plate configuration, the relative error associated with element (132547) was determined to be 0.0014%. In the case of the horizontally perforated plate, the relative error for element (362300) was recorded at 0.0332%. Regarding the vertically perforated plate, the relative error corresponding to element (296478) was found to be 0.0214%. This error measurement pertained to temperature and is presented in **Table 2.**

*Table 2 Temperature error rate in mesh test*

| No. | Elements | Temperature | Error |
|---|---|---|---|
| **Flat Plate** | 55239 | 65.05433 | 1.649821003 |
| | 76577 | 66.12761 | 0.365505422 |
| | 132547 | 66.36931 | 0.001491653 |
| | 269871 | 66.3703 | |
| **Horizontal** | 337992 | 64.86541 | 1.71300852 |
| | 341713 | 65.97656 | 0.363432104 |
| | 362300 | 66.21634 | 0.003095913 |
| | 406340 | 66.21839 | |
| **Vertical** | 272075 | 63.7659 | 1.088857838 |
| | 275801 | 64.46022 | 0.49813668 |
| | 296478 | 64.78132 | 0.006035691 |
| | 343592 | 64.78523 | |

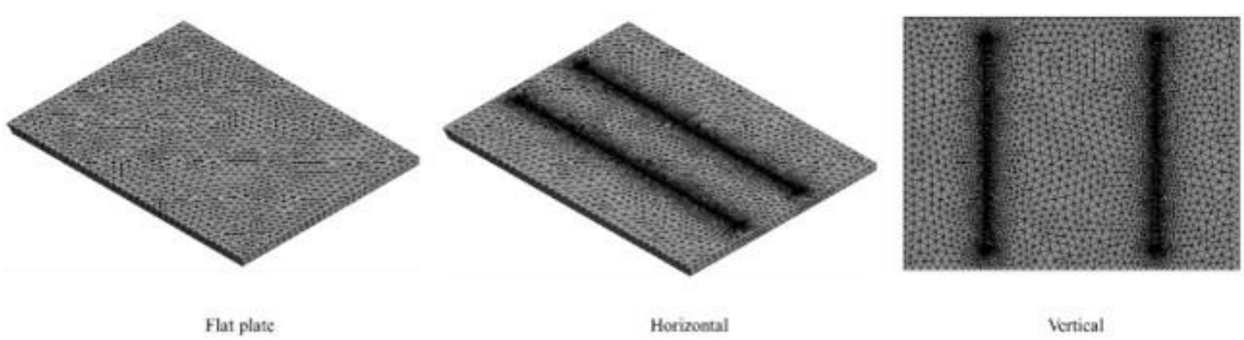


**Figure 4.** Mesh for studied models

**2.4 Temperature Contour**

As shown in the Temperature Contour figures, the temperature distribution is affected by the nature of the surface. In the case of a smooth surface (flat plate), the heat distribution is irregular due to the absence of obstacles, thus limiting the effect of heat transfer by convection. In the case of a horizontal surface, a more regular heat distribution appears, as the cracks that are in the direction of the flow help to direct the heat uniformly and gradually and reduce disturbances. In the case of a vertical surface, the cracks are against the direction of the flow, so they are a vortexcreating area, and the cracks work to improve the heat distribution. Thus, the cracks contribute to enhancing natural convection, which leads to better heat transfer from the bottom to the top.

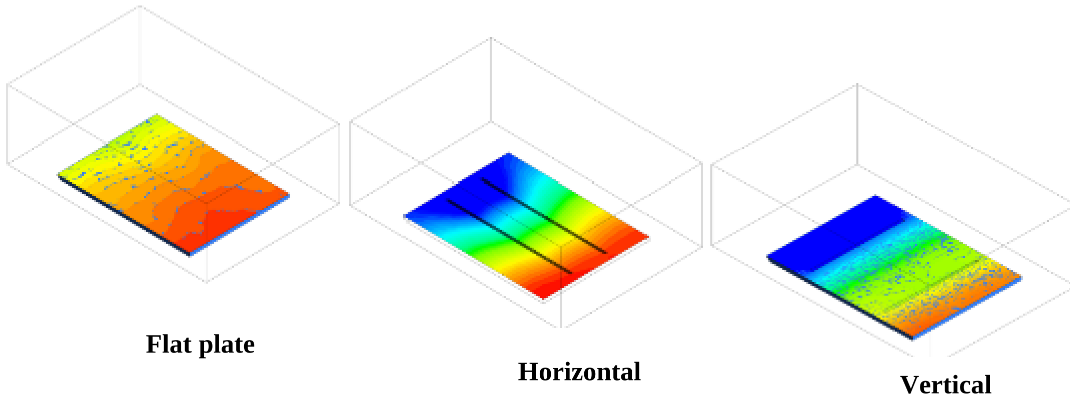


**Figure 5.** Temperature Contour.

**2.5 Airflow**

In the diagrams that show airflow, different behaviors are observed depending on the surface. In a flat plate, the flow is irregular but freer. In the case of a horizontal plate, the cracks work to distribute the air in a balanced way and reduce turbulence, so the flow is more stable and regular. In the case of a vertical plate, a stronger, more concentrated and directional flow is observed due to the cracks, which work to increase the effect of natural convection as the hot air rises through the cracks.

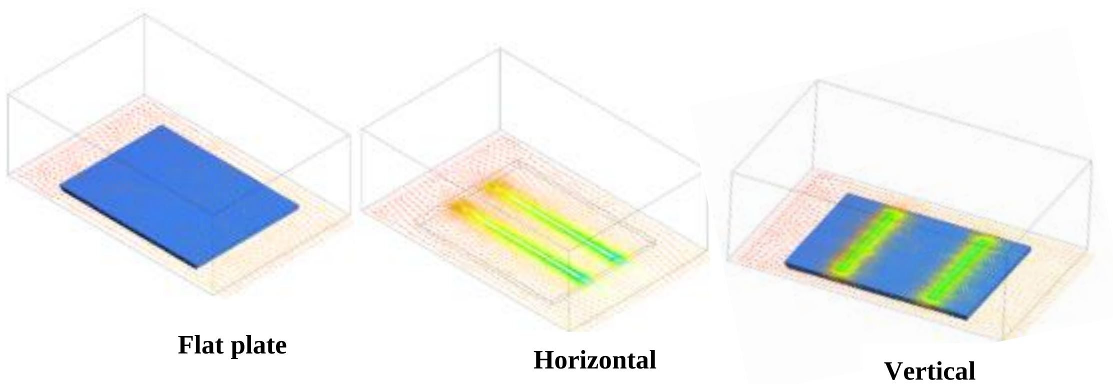


**Figure 6.** Air flow over the plate.

**3.Results and Discussion**

The convective heat transfer coefficient, usually denoted by (h), is a measure of how efficiently a fluid (liquid or gas) which transfers heat energy to or from a solid surface. In this research on semicircular grooves, h is the most important variable, as it expresses how well these grooves improve the cooling of the plate.

$$Q = h.A.(T_i - T_\infty) \qquad (9)$$

These grooves act as a **passive enhancement technique**. As air passes over the groove, a flow separation occurs, followed by a reattachment. This movement disrupts the thermal boundary layer, the thin layer that resists heat transfer. By disrupting this layer, the thermal resistance decreases, and therefore the heat gain (h) increases.

Studying the effect of the grooves, the Convective Heat Transfer Coefficient (h) was calculated for sensor number (8), as it is located in the middle of the last row of sensors. A heat transfer coefficient (h) helps in studying the effect of time or changes in operating conditions on heat transfer and the stability of thermal systems. **Figure 4** shows the results of the experimental calculations, and **Figure 5** shows the results of the ANSYS 2020 R2 calculations.

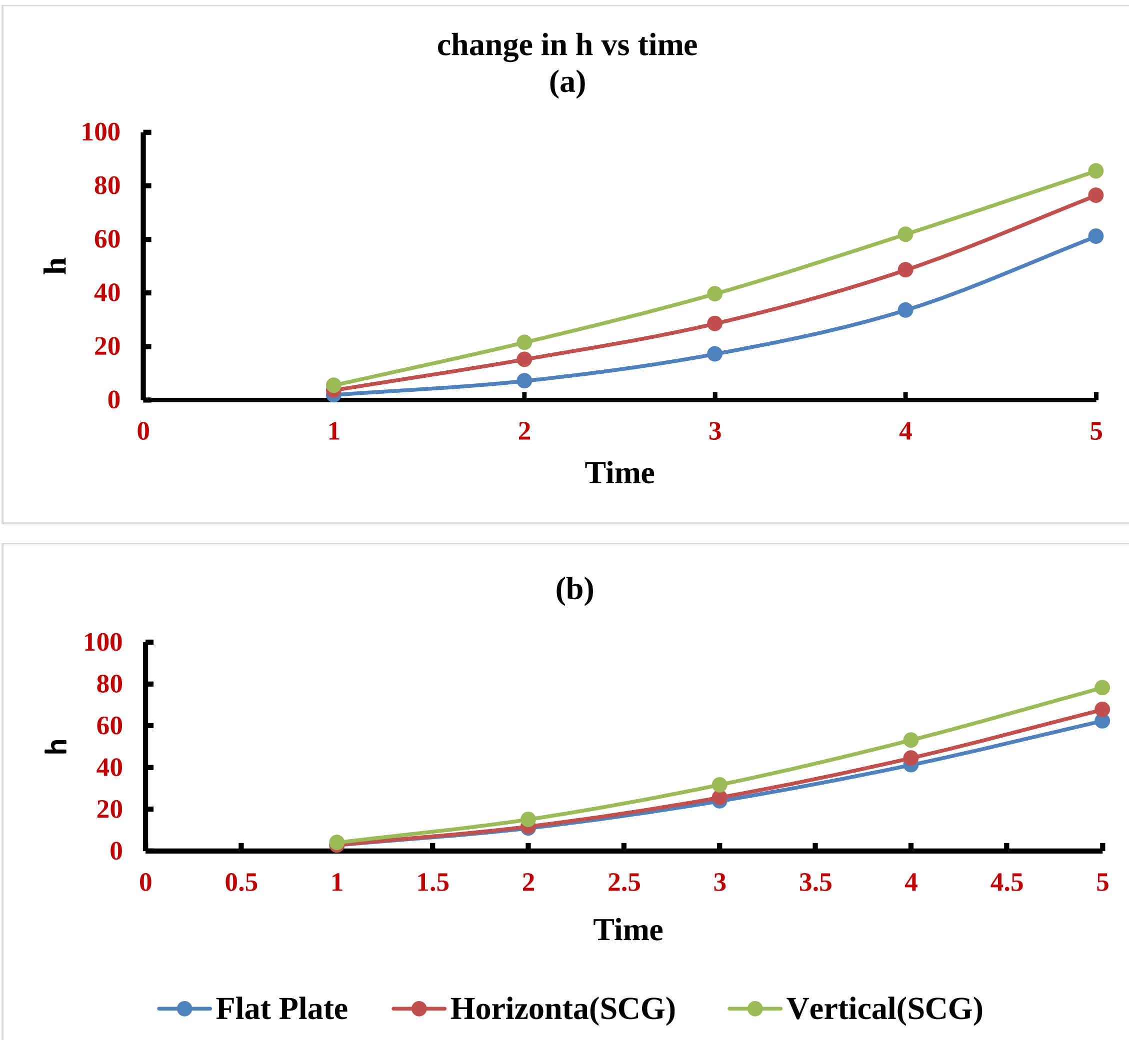


**Figure 7.** Comparison between the Experimental and the Numerical Values of h vs the time as read by the sensor No. 8. (a) Experimental. (b) Numerical.

As shown in **Figure 8**, the relationship between the temperature change measured in thermal sensor No. 8 shows that the vertical grooves have a greater effect on reducing the temperature than the horizontal grooves.

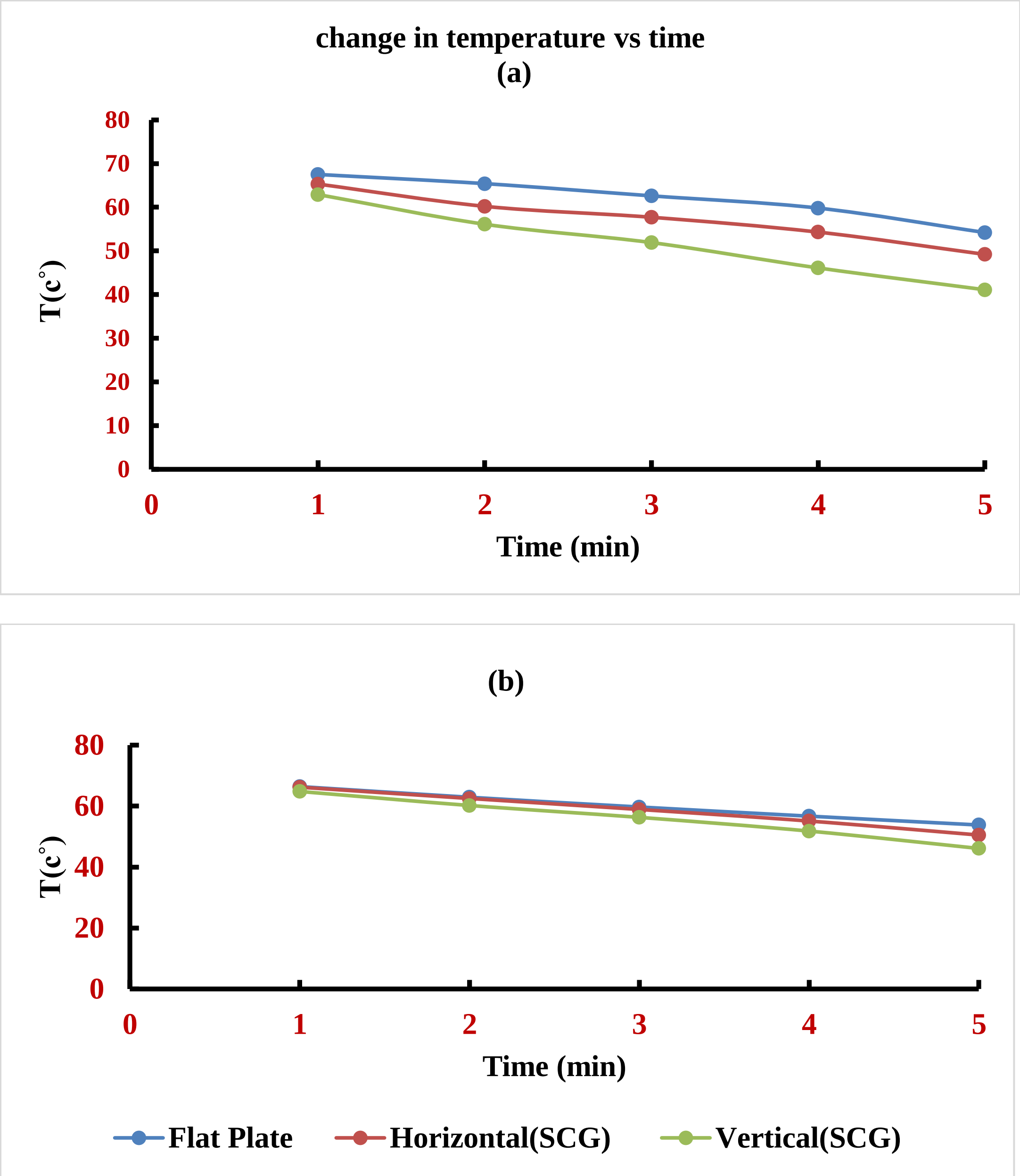


**Figure 8.** Comparison between the Experimental and the Numerical Values of h vs the time as read by the sensor No. 8. (a) Experimental. (b) Numerical.

**Comparison of Convective Heat Transfer Coefficients**

To verify the validity and accuracy of the numerical model, a comparative analysis was conducted between the experimental data and the computational fluid dynamics simulations using the following equation:

$$Error = \left|\frac{h_{exp} - h_{num}}{h_{exp}}\right| * 100\%$$

The results showed a close agreement between the two approaches, confirming that transverse grooves are effective in improving heat transfer due to their ability to increase boundary layer turbulence. The numerical results showed a slight increase compared to the experimental measurements (5–12%). The slight differences between the results can be explained as follows:

a) Experimental Uncertainties: A manometer with a measurement error was used to measure air velocity, and heat leakage was not accounted for.
b) Numerical Assumptions The inherent limitations of the (k-ω SST) model, particularly regarding flow characteristics within semicircular channels
c) Contact Resistance: The thermal contact resistance between the heater and the plate in reality, which is often treated as “ideal” in the computer simulation.

## 4. Conclusions

In the present investigation, the thermal and hydraulic efficacy of a flat plate modified with semicircular grooves aligned both vertically and horizontally in relation to the airflow direction within a wind tunnel was evaluated, and the outcomes were juxtaposed with computational fluid dynamics (CFD) numerical simulations. The ensuing results were delineated as follows:

- Enhanced Heat Transfer: In general, the incorporation of semicircular grooves engenders a notable enhancement in the heat transfer coefficient when juxtaposed with a conventional smooth flat plate. At an air velocity of 8 m/s, the vertically oriented semicircular grooves exhibited superior thermal performance.

- Physical Mechanism: The numerical findings corroborated that vertical groove facilitate the acceleration of flow separation and reattachment, consequently disrupting the formation of the thermal boundary layer. Conversely, longitudinal grooves induce secondary flow vortices that augment the mixing between the plate surface and the airstream.

- Verification: A commendable concordance was attained between the experimental data and the CFD predictions, with the maximum discrepancy remaining within an acceptable threshold (below 12%), thereby substantiating the validity of the turbulence model (k-ω SST) in forecasting complex flow dynamics over non-smooth surfaces.

- Practical implications: Experimental evidence has demonstrated that transverse grooves offer enhanced cooling performance; however, they concurrently induce a significant pressure drop. Thus, the selection of such grooves is contingent upon the specific requirements of the system in question.

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