**Numerical Study of Flow and Heat Transfer of Nanofluids in a Ribbed Channel with Winglets**

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| **Abstract**  This study numerically investigates the flow and heat transfer of CuO-water nanofluid in a ribbed channel with winglets at its center. Analyzes are performed with the Computational Fluid Dynamics (CFD) based ANSYS Fluent program. Governing equations are solved with the SIMPLE algorithm. The upper and lower surfaces of the channel consist of V-shaped ribs, and discrete V-shaped winglets are placed in the center of the channel. In the study, the nanoparticle volume fraction is kept constant at φ = 5%, and the Reynolds number (Re) varied between 100 and 600. The upper and lower ribbed surfaces are protected at a constant temperature of Tw = 360 K. The study results are given in terms of Nusselt number (Nu), and relative friction factor (r). In addition, the solutions are compared to the ribbed channel without winglets for the base fluid. The flow and temperature distributions are obtained at different Re for the ribbed channel with/without winglets. The results show that the CuO-water nanofluid and winglets contribute significantly to the heat transfer, but the friction factor is slightly increased. Nusselt number increases with increasing Reynolds number. In the channel with winglets for nanofluid flow, the heat transfer improvement is 1.32 times higher than the base fluid flow of the channel without winglets. |
| Keywords: Ribbed channel, Winglet, Nanofluids, Heat transfer, Friction factor |

1. **Introduction**

Passive methods are often used to increase heat transfer without reducing the overall efficiency of thermal devices. These methods are applications such as baffles, fins, winglets, vortex generators and ribbed/grooved surfaces in different configurations. These applications are preferred in refrigeration and air conditioning systems, transportation, nuclear reactors, heat exchangers, solar air heaters, chemical or food processing such as many fields. This method is economical compared to other techniques as it does not require external power [1-5].

Grooved channels are preferred in many engineering applications. These surfaces both increase surface area and cause self-flow oscillation. Thus, these channels have an important role in increasing thermal performance. This enhancement substantially depends on the channel geometry [6,7]. Several passive methods are used simultaneously to further improve heat transfer. Extended surfaces such as ribs/fins are generally used to increase the heat transfer area. Many studies investigated the flow and heat transfer in channel with baffles [8-10]. Promvonge et al. [11] examined heat transfer in a channel with horseshoe baffles. They declared that the heat transfer increased by approximately 92-208% and the pressure drop increased by 1.76-6.37 compared to straight channels. Kumar et al. [12] studied heat transfer of the solar air duct using multiple V-type baffles. Menni et al. [13] examined the flow and heat transfer of S-shaped baffles in the solar air duct. They reported that the highest thermal enhancement was found about 1.513 at Re = 32000 and S-downstream. Luan and Phu [14] suggested correlations for flow and heat transfer of an air heater duct with curved baffles. Bensaci et al. [15] investigated heat transfer of air heater with different baffle positions. The results shown that the highest heat transfer was obtained when the baffles were placed in the first half of the duct. Wang et al. [16] studied the effects on heat transfer of parameters such as different rib parameters, radiation intensity, mass flow rate in the solar air heater. They reported that the thermal performance of the duct with S-shaped rib increased up to 48% compared to the straight duct. Modi and Rathod [17] examined the effects of vortex generator on heat transfer in the wavy channels for 400 ≤ Re ≤ 1000. They declared that vortex shapes significantly affected the flow and thermal performance. Promvonge et al. [18] experimentally and numerically investigated the heat transfer at 4200 ≤ Re ≤ 25800 in a heat exchanger with discrete V winglets. The results reported that at a specific winglet height, the smallest pitch length ensured the highest Nu and pressure drop.

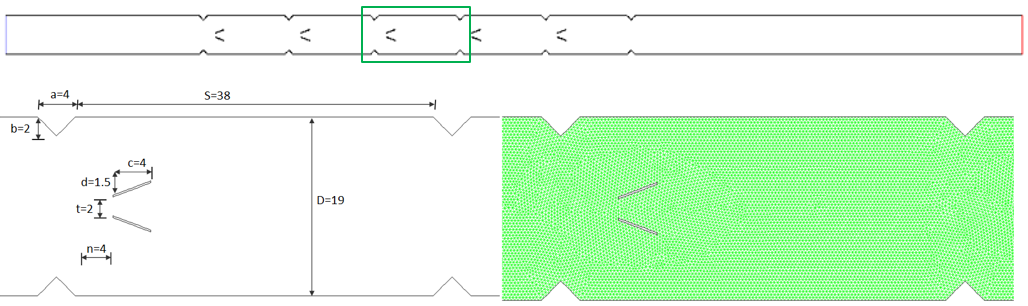
On the other hand, conventional fluids (water, ethylene glycol, and oil etc.) have low thermal properties. Nanoparticles use to increase the thermal conductivity of these fluids. Some researchers have used nanofluids together with other passive techniques [19-21]. Manca et al. [22] studied the flow and heat transfer for 20000 ≤ Re ≤ 60000 of Al2O3-water nanofluid at different rib heights and nanoparticle volume ratios (0% ≤ φ ≤ 4%) in a channel. As a result, they reported that as Re and particle volume ratio increased, the heat transfer improved, and the pumping power increased. Menni et al. [23] investigated the hydraulic and thermal performance of nanofluids in turbulent flow conditions by using baffles at different angles in the channel and reported that the highest thermal improvement was obtained when vertical baffles were used at high Re. Qi et al. [24] numerically and experimentally researched the flow and heat transfer of TiO2-water nanofluid in a wavy channel. Pordanjani et al. [25] carried out a review study examining the effects of nanofluid applications on energy savings in heat exchangers. Kaood and Hassan [26] numerically investigated the flow and heat transfer improvement and energy performance of different nanofluids in different wavy channels. They reported that nanofluids increased heat transfer according to smooth channel, and all performance improvement decreased at Re ≥ 10000 for all fluids and channel configurations. The thermal, frictional and exergy behavior of triangular vortex generator in a channel with different cross-sectional areas were examined by Tian et al. [27]. In their study, air, water and two different nanofluids (Al2O3-water and CuO-water) were used. They declared that the most thermal enhancement was obtained the circular cross section and the vortex generators enhanced significantly the Nu when the nanofluids are employed as the working fluid. However, nanofluids caused more exergy destruction as well.

As seen from previous studies, there are many experimental and numerical studies investigating the combined impact of passive heat transfer applications. However, the large number of investigated parameters increases the efforts to find the optimum parameters. As shown above, further studies on nanofluid flow in a ribbed channel with winglets are needed Effect of discrete V-shaped winglets in a V-shaped ribbed channel geometry was not investigated. In the presented study, the effects of both ribbed channel and winglets on the nanofluid flow and heat transfer were investigated together. The effects on flow and heat transfer of CuO-water nanofluid at constant particle volume fraction (φ = 0.05) under laminar flow condition (100 ≤ Re ≤ 600) in this channel were numerically examined.

1. **Materials and Methods**

**2.1. Numerical Model**

Figure 1 shows the geometry (a) and mesh structure (b) of the ribbed channel with winglets. The height of channel is D = 19 mm. At the inlet and outlet of channel, there are the unheated flat sections L1 = 5D and L2 = 10D, respectively.



a b

**Figure 1**. (a) Geometry of the numerical model (dimensions are mm), and (b) mesh structure of the ribbed channel with winglets.

Fluid is incompressible, single phase and Newtonian type. The flow is steady, 2-d, and laminar regime. Gravity and heat transfer with radiation are ignored. The governing equations are given as follows.

(1)

(2)

(3)

(4)

**2.2. Numerical Procedure**

The numerical solutions are carried out with the FLUENT 15.0 program [28]. The simulations are solved with the SIMPLE algorithm. 176144 element numbers were adopted to the numerical model. The inlet temperature of fluid is *Tin =* 300 K. The upper and lower ribbed surfaces are maintained at a constant temperature of Tw = 360 K and the winglets are defined adiabatic wall conditions. A non-slip and adiabatic boundary condition are applied for the straight section at inlet and outlet of the channel. For the validity of the solutions, the numerical results of this study are compared with the experimental study conducted by Meyer and Abolarin [29]. The agreement between the results of both studies in Ref. [30] was given.

The Nusselt number is calculated given by

(5)

where Dh is the hydraulic diameter, kf is the thermal conductivity, h is heat convective coefficient.

The average Nusselt number is calculated as follows

(6)



The friction factor (f) is defined as

(7)



where, ΔP is the pressure difference at the inlet and outlet of the channel. Relative friction factor is defined as

(8)



where f(r,w,n) and f(r) are friction factor for the nanofluids flow in the ribbed channel with winglets and friction factor for the base fluid in the ribbed channel without winglet, respectively. f(r,w) is friction factor for the base fluid in the ribbed channel with winglets. The CuO nanoparticles with the volume fraction of φ= 5% in pure water was used as the nanofluid. The thermo-physical properties of the nanofluid were calculated with the Ref. [27].

**3. Results and Discussion**

In this section, the velocity, temperature and vorticity contours were obtained in the ribbed channel with/without winglets to explain the flow and heat transfer mechanism. Figure 2 shows the velocity, temperature and vorticity contours for the base fluid in the ribbed channel without winglets at Re = 100 (a) and Re = 600 (b). It was seen that the ribbed channel structure affected the flow and temperature fields depending on Re. It was observed that with increasing Re, the fluid velocity increased, the surface temperature of the channel decreased, and the longitudinal vortex structures increased due to the cross-section narrowing in the grooved sections.

Figure 3 indicates the velocity, temperature, and vorticity contours in the CuO-water nanofluid at φ=0.05 in the ribbed channel with winglets for Re=100 (a), and Re=600(b). The winglets have changed the flow and temperature fields depending on Re. The winglets directed the cold fluid towards the channel surfaces and flow oscillations occurred in the channel. Due to the winglets, the temperature gradient on the channel surfaces decreased considerably with increasing Re, the seconder flow loops were concentrated throughout the channel, and the heat transfer was improved due to a homogeneous flow mixing.

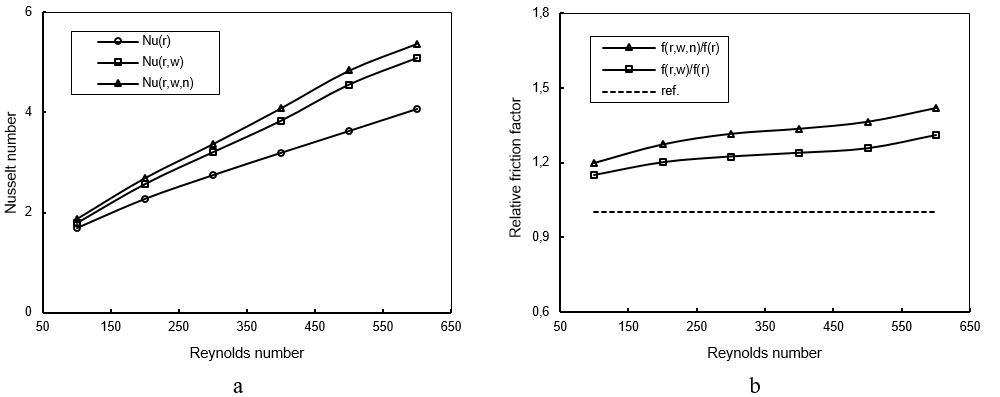
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| Re=100, velocity contour, base fluid |
| Re=100, temperature contour, base fluid |
| Re=100, vorticity contour, base fluid |
| (a) |
| Re=600, velocity contour, base fluid |
| Re=600, temperature contour, base fluid |
| Re=600, vorticity contour, base fluid |
| (b) |

**Figure 2.** Thevelocity, temperature and vorticity contours for base fluid in the ribbed channel without winglets**,** a) Re=100, b) Re=600.

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| Re=100, velocity contour, φ=0.05 |
| Re=100, temperature contour, φ=0.05 |
| Re=100, vorticity contour, φ=0.05 |
| (a) |
| Re=600, velocity contour, φ=0.05 |
| Re=600, temperature contour, φ=0.05 |
| Re=600, vorticity contour, φ=0.05 |
| (b) |

**Figure 3.** The **v**elocity, temperature and vorticity contours for CuO-water nanaofluid at φ=0.05 in the ribbed channel with winglets**,** a) Re=100, b) Re=600.

Figures 4a and 4b show Nu (a) and the relative friction factor (b) with Re in the ribbed channel with/without winglets for the nanofluid and base fluid flow, respectively. The dashed line represents the base fluid for the ribbed channel without winglets. Nu(r,w,n) is Nu for the nanofluids flow in the ribbed channel with winglets, Nu(r,w) is Nu for the base fluid in the ribbed channel with winglets, and Nu(r) is Nu for the base fluid in the ribbed channel without winglet. From Figure 4a, it is visible that the Nusselt number increases with increasing Re for all channel structures. The highest Nu was found to be about Nu = 5.38 in the ribbed channel with winglets for Re = 600 and φ=0.05. In the ribbed channel with winglets for CuO-water nanofluid flow, the heat transfer improved by about 1.32 compared to the ribbed channel without winglets for base fluid. Although heat transfer is increased with the addition of winglets, the pressure drop within the channel also increases due to the decreasing flow field effects. It can be visible in Figure 4b that the relative friction factor increases as the Re increases compared to the channel without winglets. The highest relative friction factor was obtained to be about 1.42 for Re = 600 and φ = 0.05.

**Figure 4.** a) Nusselt number, b) Relative friction factor with Re.

**4. Conclusion**

In the present study, the heat transfer and friction factor of CuO-water nanofluids flow in a ribbed channel with/without winglets were investigated numerically. The study was also compared to the base fluid of the ribbed channel without winglets. The velocity, temperature, and vorticity contours were presented in the channel to understand the flow and heat transfer behaviors. The results of the study indicated that the contours were highly influenced by channel geometry. There is a significant effect of winglets and CuO-water nanofluid on heat transfer improvement. In the channel with winglets for nanofluid flow, the heat transfer is 1.32 times higher than the base fluid of the channel without winglets. The relative friction factor increased with Re. CuO-water nanofluid in the ribbed channel with winglets provided considerable improvement in heat transfer, while an acceptable increase in friction factor was seen. The highest Nu was obtained as 5.38 at Re = 600 and φ = 0.05. The highest relative friction factor was found to be 1.42 at Re = 600 and φ = 0.05.

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