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COMPUTATIONAL FLUID DYNAMICS AND EXPERIMENTAL ANALYSIS OF A CORRUGATED PLATE DUCT

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Abstract

Superior heat transfer at a lower fluid velocity is possible in a corrugated plate heat exchanger because local turbulence is created by breaking of the laminar sub-layer. Corrugated compact heat exchanger may be used for waste heat utilization from exhaust of an engine at a variable mass flow rate. Computations on heat transmission and fluid movement were conducted on a heated corrugated duct. Experiments were accomplished for analysis of air temperature rise in the corrugated and plain plate ducts. Numerical results showed that Nusselt number, pressure drop had increased with intensification of airflow rate and skin friction coefficient had decreased. At an airflow rate of 0.05 kg/s, the temperature of the corrugated and flat plates dropped from 420 K to 373 K, 387 K. At mass flow rate 0.013 kg/s temperature dropped to 380 K to 392 K for corrugated and the flat plate. Average Nusselt numbers were 160, 45 for mass flow rates of air 0.05 kg/s and 0.002 kg/s. Average pressure drops through the corrugated duct were 30 Pa and 2.5 Pa for the corresponding air mass flow rates.

Keywords*:* Corrugated heat exchanger, Nusselt number, Turbulence, Pressure drop, Mass flow rate

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1. Introduction

A heat exchanger is a mechanical assembly for transmission of heat between minimum two fluids, a solid surface with a fluid, at dissimilar temperatures and thermal interactions. The importance for the development of efficient heat exchangers has matured with the characteristic of energy preservation, transformation, retrieval, and effective enactment of innovative energy destinations. Extraordinary heat-transfer superficial area to volume ratio is a controlling parameter for the design of a concise heat exchanger. It has established noticeable thoughtfulness because of the superior heat transfer coefficients linked to its counterpart's conventional heat exchangers. Research has reported to attain heat exchanger with high effectiveness, low-pressure losses, low weight, and volume, high reliability. As a result, heat exchangers contain the special geometries like corrugated, wavy and curved flow ducts or channels with variable cross-sectional areas for an enhanced heat transfer rate. Numerical and experimental studies are available for exploration of the interface between flow performance and consequential thermodynamics through optimization and design for the improved units.
Numerous systematic studies are available on the system, examination, enactment, and assessment of heat exchangers. They explored a variety of topics such as geometric attributes, efficacy, presentations, and the relative assessment of heat exchanger category, etc.

Numerical study of corrugated plate heat exchanger:

Abdel-Aziz et al. (2013) considered liquid-solid mass transmission behaviour of V-ribbed faces in two-phase flow. Abed et al. (2015) investigated on the improvement of heat transfer in a channel with V- profile wavy plate using liquid nano-fluids. At Reynolds number (Re) 8000–20,000, SiO_2 nanofluid yielded the best heat transfer improvement. Akdag et al.(2017) numerically investigated heat transfer augmentation with the nano-fluids under laminar flow in a trapezoidal grooved duct. An exciting flow situation of nanoparticles had increased the heat transfer proportion.Anandan and Bhaskaran(2012) investigated on the thermal and economic study of a pipe heat exchanger (PHE) for waste heat retrieval by NTU method. The best efficacy of an PHE was represented by a polynomial relationship. Ayyappan et al. (2012) studied on a solar tunnel dryer with a heat reservoir for dehydration of copra. Thermal efficiency of the dryer was found 15% only.Dhiman et al. (2015) reported the consequence of thermal enactment of recurrent double-pass flat and V grooved solar air heaters.

Deshmukh et al. (2017) made an experimental investigation on a hybrid solar system with a special heat exchanger. The result showed that thermo-syphon method was ideal for production of electricity and hot water. Doo et al. (2012) studied on intersecting heat exchanger with corrugation faces for an innovative intercooled-sequence aircraft prime mover. It allowed the growth of lightweight and better performed intercoolers. Fernandes et al. (2007) made an investigation on laminar flow in a ribbed plate heat exchanger. Low Reynolds number flow was reported when high viscosity liquid flowed through the plate heat exchangers. Gao et al. (2017) made a numerical study on the turbulent flow in a cross-corrugated triangular channel having delta-profile baffles. Hussain et al. (2013) computationally explored the free convection thermal interaction of airflow in a corrugated attachment with an inclined heated plate. The Nusselt number increased in line with the Rayleigh number. Lin et al. (2006) studied thermal enactment of a cross- ribbed solar air collector parametrically. Absorber contained a wavy collector and the lowermost plate. It was transversely situated for the arrangement of airflow channel. Sherony et al. (1969) performed an analytical study of heat, mass transfer, and friction factor in a corrugated channel heat exchanger. They compared friction factor and the Nusselt number for the sinusoidal and triangular profiles. Liu et al. (2014) made an investigation on the optimal design technique for the heat recovery units in a building. Yang et al. (2006) investigated on fluid flow and heat transfer characteristics in a heated V corrugated ducts. They perceived that increased in angle of V corrugated plates gave better heat transfer.

Experimental study of corrugated plate heat exchanger:

Islamoglu et al. (2003) made a study on consequence of the conduit height on heat transfer efficacy. Nusselt number intheribbed duct was more than the conventional one. Khan et al.(2010) made an investigation on ammonia evaporation in a diverse arrangement of V-shaped plate heat exchanger. Thermal performance increased with oil fraction (0 to 3) % only. Beyond this oil fraction, the thermal performance declined. Kilic et al. (2016) explored the heat transfer and efficacy in a grooved plate heat exchanger with dissimilar corrugation angles. The chevron angles were taken as 30^0 and 60^0. They observed that at 60^0 corrugation angles, heat transfer rates and effectiveness were higher. Li et al. (2008) made an experimental analysis of a distinctive thermoelectric household duct with heat retrieval. The performance of the ventilator was expressed as a coefficient of performance (COP). The COP was recorded over 2.5 form the experiment. Mohammed et al. (2013) made an investigation on the influence of constraints of geometry in a grooved conduit with out of stage configuration. They studied the effects of groove slope, duct, and curly heights. The investigation covered Reynolds number and heat transfer from 8000 to 20000 and 0.4-6 kW/m^2. Optimum parameters were groove angle of 60°, altitude of 2.5 mm and duct altitude of 17.5 mm. Naphon et al. (2007) made an experimental exploration on thermo-hydraulic study in a grooved conduit at constant heat flow. The Nusselt number improved with an augmentation of wavy angle. Naphonet al.(2009) made an experimental analysis of curvy geometry arrangements of a plate on the temperature and stream disseminations. The temperature gradients amplified with enhancement of airflow rate. Pandey et al. (2011) deliberated the thermo-hydraulic study in a grooved plate heat exchanger. The effectiveness of this ribbed PHE was found as 82%. Pehlivan et al. (2013) made an experiment on the heat transfer rate for a sinusoidal grooved channel. Selvaraj(2012) studied on energy preservation in an aluminium-processing unit using waste heat from solidifying molten metal. About 16 % of heat recovery was possible. Various solar thermal transformation devices are available. Tiwari et al. (2014) studied on combined energetic and exergetic efficiency of a grooved plate heat exchanger. The exergetic efficiency enhanced with the Reynolds number. Dutta et al. (2019, 2017, 2014, 2021) had studied energy effective solar dryer, compact corrugated heat exchanger, miscellaneous air heaters like flat plate, corrugated plate for solar drying applications. Sharma et al. (2019) examined aluminium can solar air heater. They noted that thermal enactment of the aluminium solar air heater was superior in terms of thermal efficiency and outlet air temperature. Begum et al. (2021) studied parabolic trough collector for cleansing of drained water. Dutta and Goswami(2021) evaluated thermal enactment of two different arrangements of solar air heater's absorber plates in the actual climatic condition of Tezpur, Assam, India.

Based on above literature review, the objective of the present work is fluid flow and heat transfer study of a sinusoidal corrugated aluminium duct at a particular boundary condition given by Table: 2.

2. Mathematical Formulation

The present numerical and experimental studies consider fluid flow and heat transfer features in a sinusoidal corrugated plate duct.

Numerical analysis

Computational Fluid Dynamics and Experimental Analysis of a Corrugated Plate Duct

The numerical study was performed in a professional code of ANSYS FLUENT 13.0. In the first part of the analysis, 2D heat transfer was explored in a 20 mm height sinusoidal duct. The effects of mass flow rates on the Nusselt number, pressure drop and skin friction coefficient are presented for corrugated plates with a channel height of 20 mm. The variations of the parameters were studied for the mass flow rates of 0.002, 0.009, 0.013 and 0.05 kg/s respectively. The fluid used in the analysis is air. The density of air was 1.225 kg/m^3 and it was allowed flowing through these corrugated plates ducts. The variation of Nusselt number and pressure drop along the plates were studied.

Experimental methodology

Experiments were performed for learning the consequence of corrugation on heat transfer efficacy. The comparisonwas made for heat transfer in a corrugated sinusoidal plate and a plain plate. Components used in the setup were, hot wire anemometer, K-type thermocouple, variable speed air blower, heater plate, corrugated plate, plain plate, temperature data logging with a computer interface.

The height of corrugation of the corrugated plate used was 10 mm and pitch is 75 mm. The width of the plate was 150 mm. The channel is of height 20 mm and of length 275 mm. There was a converging and a diverging channel beforehand and afterward the test section respectively for stabilization of the fluid flow. The air blower was connected to the diverging channel and the air is blown through the channel. The air was then passed over the heated corrugated plate. Eight thermocouples were placed in the walls of the channel and they were connected to the temperature data logging system. Temperature readings were taken for two different mass flow rates. A plain plate then substituted the corrugated plates. The identical process was continued, and readings were taken for two mass flow rates. The experimental results for the corrugated plates were further compared with that of the numerical analysis that was performed in ANSYS FLUENT 13.0.

Capabilities of ANSYS FLUENT

ANSYS FLUENT solves the governing integral equations for the conservation of mass, momentum, energy and other scalars such as turbulence. A control-volume based technique is used that consists of following steps. A grid is generated on the domain in the pre-processing part. For velocity, pressure, temperature, and conserved scalars, algebraic sets of equations are constructed by integration of the governing equations on each control volume. 2D/3D geometrical modelling of the control volume is performed. Appropriate boundary conditions are imposed as per the geometry of the analysis. Convergence criteria are fixed for the steady or unsteady equations. Discretized partial differential equations are linearized and solved iteratively. Through post processing, results in terms of velocity, temperature, pressure, fluid flow path are represented in graphical form for the audience. Experimental research in fluid flow and heat transfer for complex engineering system is expensive, sluggish, successive, and single-purpose. At the other hand, simulation with ANSYS FLUENT computational fluid dynamics (CFD) is comparatively of low cost, faster, parallel, and multi-purpose. CFD simulation is not 100% accurate because the input condition may have excessive guessing or uncertainty. At the other hand, the mathematical model considered may not be sufficient. Accuracy of results depends on computing capabilities and appropriate boundary conditions imposed. SIMPLE algorithm was used for pressure and velocity coupling; second order upwind scheme was for momentum.

Mathematical modelling

The governing equations are continuity, momentum, and energy equation. The equations are given as Akdag et al. (2017):

$$\frac{\partial}{\partial x_i}(\rho v_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho v_i v_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i})] - \frac{2}{3}\mu\frac{\partial v_k}{\partial x_k}\partial_{ij}] \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho v_j C_p T - k\frac{\partial T}{\partial x_j}) = u_j\frac{\partial p}{\partial x_j} + \mu\left(\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial v_i}\right) - \frac{2}{3}\frac{\partial v_k}{\partial x_k}\partial_{ij}\right) \tag{3}$$

The current analysis deals with the typical *k*-*ε* model. The boundary settings executed on the corrugated plate were no slip and zero heat flux, as they were thermally shielded. The flow was assumed turbulent and incompressible. Airflow limiting environments were applied at the inlet while, pressure limiting environment were put at the outlet.

The governing equations for the standard *k*-*ε* model are:

$$\frac{\partial}{\partial x_i}(\rho k v_i) = \frac{\partial}{\partial x_j}[(\frac{\mu+\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}] + \mu_t\left[\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial v_i}\right]\frac{\partial v_i}{\partial x_j} - \rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon v_i) = \frac{\partial}{\partial x_j}[(\frac{\mu+\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}] + C_{1\varepsilon}\frac{\varepsilon}{k}\mu_t\left[\frac{\partial v_i}{\partial v_j}+\frac{\partial v_j}{\partial v_i}\right]\frac{\partial v_i}{\partial v_j} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - \alpha\rho\frac{\varepsilon^2}{k} \tag{5}$$

Modelling the Turbulent Viscosity:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

Constants are $C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3$ (7)

The values of the constants have been decided from the experiments for ultimate turbulent flows, with normally happened shear flows kind border layers, mingling layers and jets and for decomposing isotropic grid instability as well. It worked impartially fine for an extensive variety of wall-bounded and unrestricted shear flows.

Grid convergence test

Grid convergence is used to define the progress of results by using continuously smaller cell sizes. It should tend to the precise result as the mesh become finer. The normal CFD practice is to start with a coarse mesh and progressively refine it until the changes detected in the results are smaller than a predefined tolerable error (Table 1).

Table 1 Grid independency test

Refining levels	Number of elements	Percentage variation of air temperature	Percentage variation pressure drop
1	100000	4.5	5.5
2	150000	3.5	3.4
3	300000	0.52	0.70
4	360000	0.43	0.60

For the assessment of corrugated duct, in order to evaluate the accuracy of the numerical technique, the domain for a 2D channel length 275 mm, width 150 mm, channel height 20 mm and corrugation height 10 mm was tested. To apprise the number of elements required, four different meshes were verified. The grid independence test was supported out in the analysis by accepting dissimilar grid elements as shown in Table1. The grid independence tests show that the grids of 300000 elements guarantee an acceptable solution. It is clear that after 300000 there is not noteworthy percentage difference in the appraised parameters. The experimental setup is presented in Fig.1a and Fig.1b.

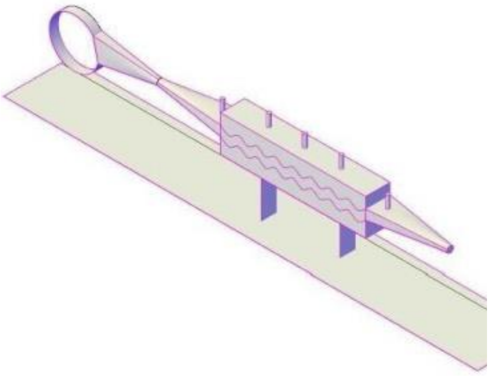

Fig.1a: Isometric view of experimental setup

Fig.1b: Computerized experimental setup

Boundary conditions

The boundary conditions applied for simulation of the corrugated duct are presented in Table: 2 below.

Table 2 Boundary conditions applied for simulation studies:

Boundary region	Type of region	Air mass flow rate (kg/s)	Pressure (Pa)	Temp. (K)	Heat flux (W/m^2)
Inlet	Velocity	0.002 – 0.05	101315	305	Adiabatic
Outlet	Pressure	Out flow	101275	350	
Duct wall	Wall	No slip	-	-	
Absorber	Wall	No slip	-	420	1000

3. Results And Discussion

For numerical analysis, ANSYS FLUENT was used for attaining simulated outcomes representing various physical attributes that influenced the flow and heat transfer in the corrugated duct. The numerical computations were performed by solving the governing conservation equations alongside the boundary environments.

Outcome of airflow rate on flow and heat transfer attributes in a grooved plate:

Figures 2, 3 and 4 show the change of Nusselt number, pressure drop, skin friction for different mass flow rates along a channel of 20 mm channel height. From Fig.2, it may be observed that the variation of Nusselt number is more in the converging segment at every flow velocity than in the diverging unit. Since the converging segment has a greater average velocity, it enhances the heat transfer ratio. Fig. 3 shows that pressure drop decreases in the region with a minimum cross-section because in these regions, the velocity of flow increases. With an increase in air mass flow rate, pressure drop increases. The maximum average pressure drop is 30 Pa for 0.05 kg/s mass flow rate, 2.5 Pa for 0.002 kg/s mass flow rate. As expected skin friction coefficient had decreased with an increase in mass flow rate is represented in Fig. 4.

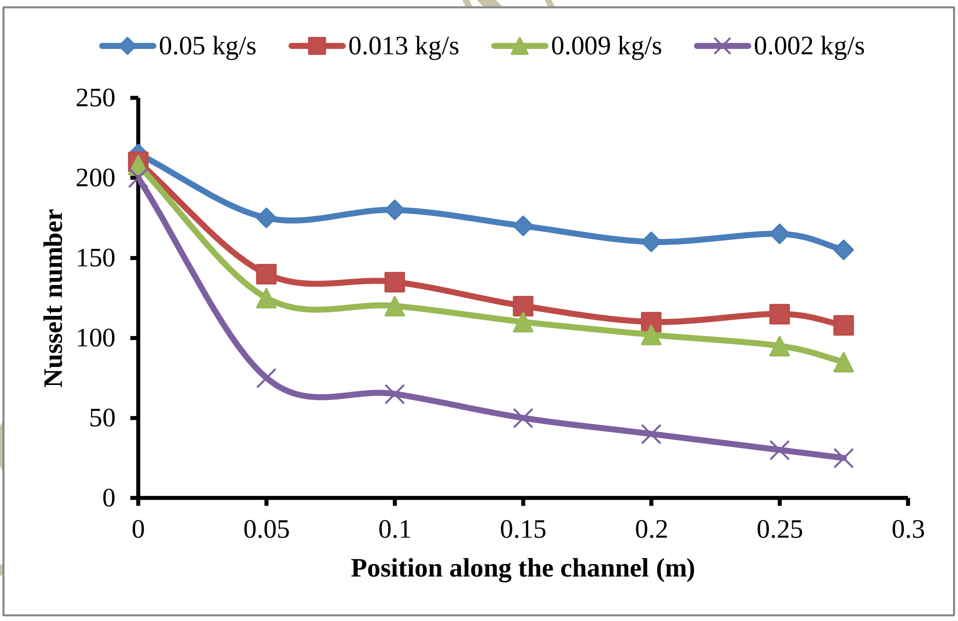

Fig. 2: Change of Nu at various air flow rates

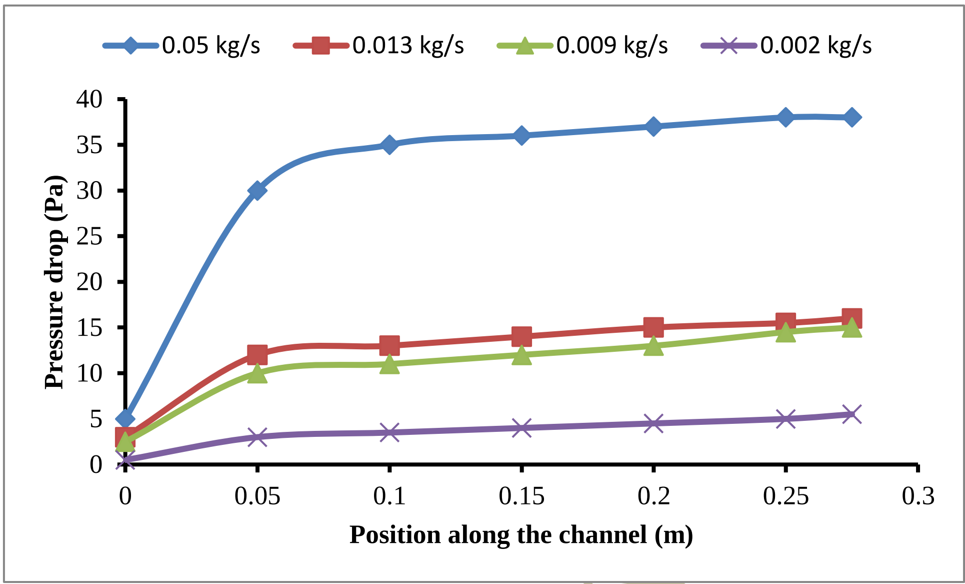

Fig. 3: Change of pressure drop lengthwise

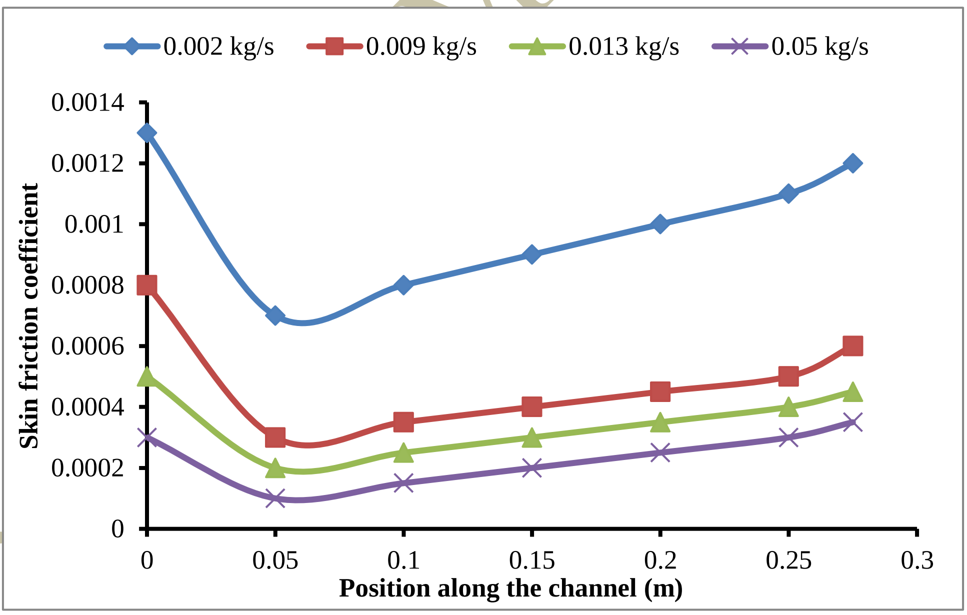

Fig. 4: Change of Skin friction coefficient lengthwise

Experimental analysis:

An electric heating coil through corrugated plate heated air from the variable speed blower. At first, the airflow rate was 0.013 kg/s. The temperature was measured at various axial points along the channel at a distance of 37.5 mm. The temperature readings were taken from the temperature data logging system for both the corrugated plate and plain plate. The maximum experimental and computational air temperatures of the corrugated channel are 355 K and 360 K.

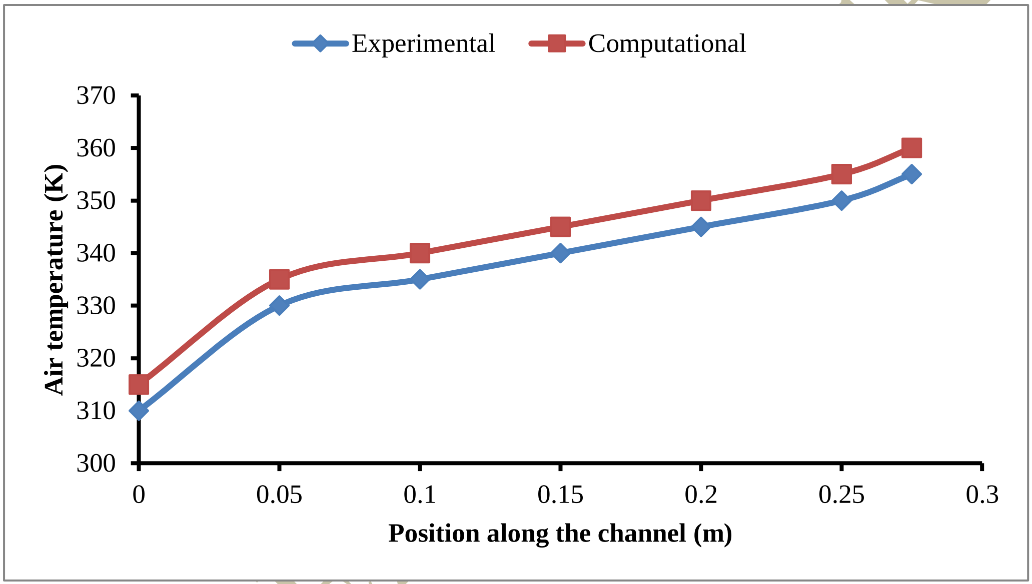

Fig. 5: Experimental and computational results of air temperature for the corrugated channel at 0.013 kg/s

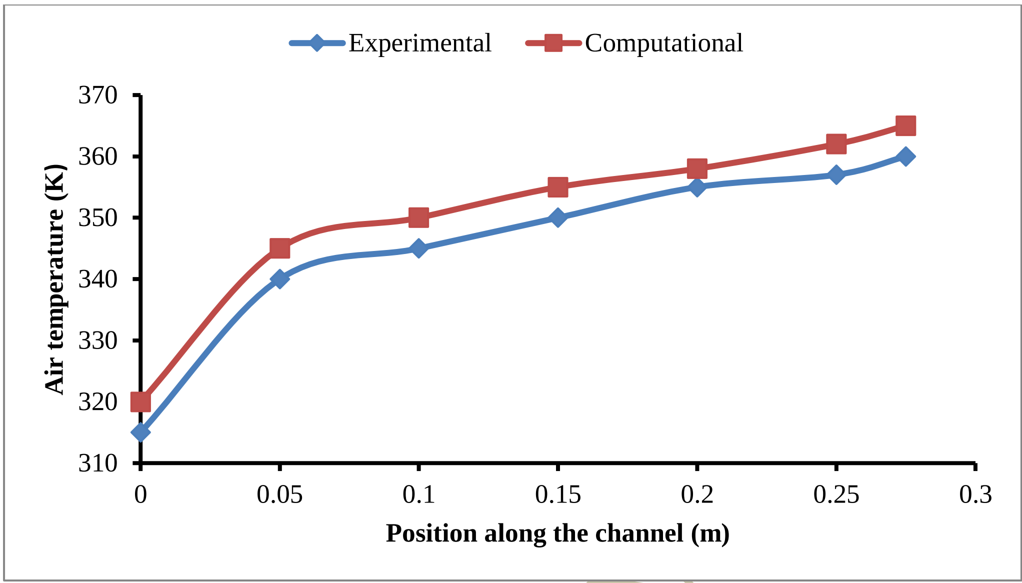

Fig.6: Experimental and computational results of air temperature for the corrugated channel at 0.05 kg/s

Appraisal of experimental and computational results for grooved plate:

Experimental data acquired from the data logging system were compared with that of the numerical results of ANSYS Fluent. They are presented in Fig. 5 and Fig.6. The temperature distribution is plotted against axial distance from the inlet along the channel. The experimental curve is in the decent settlement with numerical results. The maximum experimental and computational air temperatures of the corrugated channel are 360 K and 365 K for mass flow rate of 0.05 kg/s.

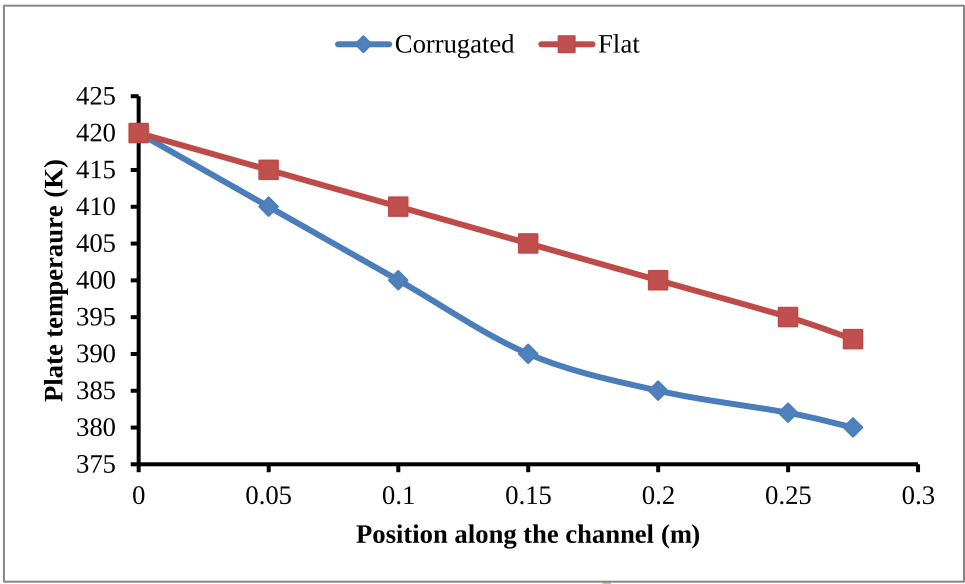

Fig. 7: Temperature distribution along corrugated and plain plates at 0.013 kg/s

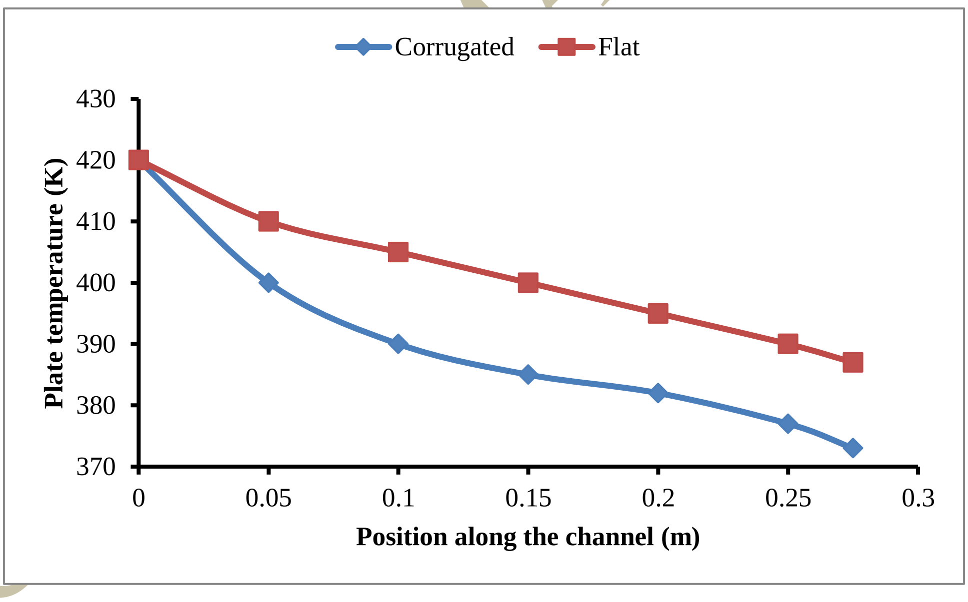

Fig.8: Temperature distribution along corrugated and plain plates at 0.05 kg/s

Appraisal of corrugated and plain plate achievable temperatures:

An appraisal of temperature distribution of the corrugated and the plain plate was made. Two airflow rates of 0.013 kg/s and 0.05 kg/s were taken. The temperatures of the air at the inlet were 420 K. Fig. 7 and Fig. 8 show that, with the same inlet temperature for both the plates; the outlet temperature of the corrugated plate is lower in comparison to that of the plain plate. That means there is more heat transfer when corrugated plates are used than that of the plain plate. When the airflow rate is 0.013 kg/s and inlet temperature is 420 K, the outlet temperature of the corrugated plate is 380 K and that for the plain plate is 392 K. When the mass flow rate is 0.05 kg/s and inlet temperature is 420 K, the outlet temperatures are 373 K and 387 K for the grooved and plain plates.

4. Conclusions

A two-dimensional heat transfer analysis was explored in a sinusoidal conduit having the duct height of 20 mm. An assessment of temperature distribution between the corrugated and the plain plate was madenumerically and experimentally.

- Nusselt number, pressure drop augmented with rise in airflow rate.
- Forthe same inlet temperatures in both the plates, the outlet temperatures for the corrugated plate were lower in comparison to that of the plain plate.
- When the airflow rate was 0.013 kg/s and inlet temperature was 420 K, the outlet temperature of the corrugated plate was 380 K and that for the plain plate was 392 K.
- When the mass flow rate was 0.05 kg/s and inlet temperature was420 K, the outlet temperature of the corrugated plate was373 K and that for the plain plate was 387 K.
- As the temperature drop was more for the grooved plate, therefore the heat transfer rate was enhanced.
- Temperature drop increased by 3.15 % for 0.013 kg/s airflow rate and 3.62 % for 0.05 kg/s airflow rate with the corrugatedplate.

- ❖ Temperature drop deviations were 1.38 % for 0.013 kg/s and 1.11 % for 0.05 kg/s air flow rates for the experimental results with respect to numerical results.

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