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Computational Fluid Dynamics Analysis Of Heat Transfer And Friction Characteristics In Solar Air Heater With Staggered Inclined Discrete Rib Roughness

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ABSTRACT
This research investigates the heat transfer and friction characteristics in a rectangular duct solar air heater with staggered inclined discrete rib roughness on the absorber plate. The study employs Computational Fluid Dynamics (CFD) to analyze the effect of relative roughness pitch (P/e) on thermal performance. A 3D CFD model was developed using ANSYS Fluent 14.5 with the Renormalization-group (RNG) k-ε turbulence model. Simulations were conducted for Reynolds numbers ranging from 2000 to 16000 with relative roughness pitch values of 8, 9, 10, and 11. Results demonstrate that the thermal performance increases with Reynolds number, and the optimal relative roughness pitch is P/e = 10, which yields the maximum Nusselt number enhancement of 2.58 times compared to smooth ducts. The maximum enhancement in friction factor is 3.86 times at the same pitch value. The highest thermohydraulic performance parameter of 1.99 was achieved at a Reynolds number of 12000 with P/e = 10. These findings contribute valuable insights for designing more efficient solar air heaters with artificial roughness elements.

Keywords
Solar air heater, CFD analysis, Staggered inclined discrete rib, Heat transfer enhancement, Turbulence, Relative roughness pitch, Friction factor, Thermal performance

1. INTRODUCTION

Solar energy represents one of the most promising renewable energy sources due to its abundance and environmentally friendly nature. Solar air heaters are simple, cost-effective solar thermal systems that convert solar radiation into thermal energy by heating air flowing through a duct. However, the inherently low heat transfer coefficient between the absorber plate and flowing air results in poor thermal efficiency of conventional solar air heaters. This limitation necessitates the development of techniques to enhance heat transfer rates for improving the overall performance of solar air heaters.

Artificial roughness in the form of ribs on the underside of the absorber plate has been established as an effective passive heat transfer enhancement technique. These roughness elements break the laminar sub-layer and create local wall turbulence, which reduces thermal resistance and enhances heat transfer. Various researchers have investigated different roughness geometries, including transverse, inclined, V-shaped, and discrete ribs. However, the increased heat transfer is accompanied by an increase in friction factor, resulting in higher pumping power requirements. Therefore, it is essential to determine the optimal roughness configuration that provides maximum heat transfer enhancement with minimal friction penalty.

The present study employs Computational Fluid Dynamics (CFD) to investigate the effect of relative roughness pitch (P/e) on heat transfer and friction characteristics in a solar air heater duct with staggered inclined discrete rib roughness on the absorber plate. This research aims to identify the optimal configuration that maximizes thermal performance while minimizing the associated pressure drop.

2. METHODOLOGY

2.1 Physical Model and Computational Domain

The physical model consists of a rectangular duct with staggered inclined discrete ribs placed on the absorber plate. The computational domain is divided into three sections: entrance section, test section, and exit section. The top wall of the duct comprises a 0.5 mm thick aluminum absorber plate with artificial roughness in the form of staggered inclined discrete ribs arranged at an angle of 45° to the flow direction. The remaining walls are kept smooth. A uniform heat flux of 900 W/m^2 is applied to the top wall of the test section, while the bottom wall is maintained at adiabatic condition.

The geometric parameters investigated include a fixed rib height (e) of 2 mm, relative roughness height (e/Dh) of 0.045, rib width (b) of 2 mm, angle of attack (α) of 45°, and relative gap width (g/e) of 1 mm. The relative roughness pitch (P/e) is varied from 8 to 11 to study its effect on thermal performance. The relative gap positions (dt/W and dl/W) are fixed at 0.3 and 0.4, respectively. The flow Reynolds number is varied from 2000 to 16000 to cover the range commonly encountered in solar air heaters.

2.2 Numerical Modeling and Simulation

A three-dimensional CFD model was developed using ANSYS Fluent 14.5. The governing equations of continuity, momentum, and energy were solved using the finite volume method in steady-state conditions. The Renormalization-group (RNG) k-ε turbulence model was employed to simulate the turbulent flow, as it has been validated for similar flow conditions in previous studies. The SIMPLE algorithm was used for pressure-velocity coupling, and second-order upwind scheme was chosen for discretization of momentum and energy equations.

A grid independence test was conducted to ensure that the solution is independent of grid size. The final mesh consisted of 70,478 tetrahedral elements with 90,458 nodes. The convergence criteria were set at 10^{-3} for continuity equation residuals, 10^{-6} for velocity component residuals, and 10^{-6} for energy equation residuals. Uniform velocity profiles were specified at the inlet, while pressure outlet conditions were applied at the exit. No-slip boundary conditions were imposed on all solid surfaces, and the turbulence kinetic energy was set to zero on all walls.

3. DATA COLLECTION

The numerical simulations were performed for various combinations of Reynolds numbers and relative roughness pitch values. For each configuration, the following data were collected:

1. Temperature distribution along the duct
2. Velocity field and flow patterns
3. Pressure drop across the test section
4. Heat transfer coefficient at the absorber plate
5. Turbulence intensity in the flow field

From these primary data, secondary parameters such as Nusselt number, friction factor, and thermohydraulic performance parameter were calculated. The Nusselt number represents the ratio of convective to conductive heat transfer across the boundary, while the friction factor characterizes the pressure drop in the duct. The thermohydraulic performance parameter evaluates the overall effectiveness of the roughness geometry by considering both heat transfer enhancement and friction penalty.

Table 1 presents the key geometric and operating parameters used in the CFD simulations. The data collected from these simulations were used to analyze the heat transfer and friction characteristics of the solar air heater duct with staggered inclined discrete rib roughness.

Table 1: Geometric and Operating Parameters for CFD Analysis

Parameter	Description	Value/Range
e	Rib Height	2 mm
P	Rib Pitch	16, 18, 20, 22 mm
P/e	Relative Roughness Pitch	8, 9, 10, 11
b	Rib Width	2 mm
g/e	Relative Gap Width	1 mm
α	Angle of Attack	45°
e/Dh	Relative Roughness Height	0.045
Re	Reynolds Number	2000-16000
dt/W & dl/W	Relative Gap Position	0.3 & 0.4
I	Heat Flux	900 W/m²

4. DATA ANALYSIS

The heat transfer and friction characteristics were analyzed by calculating the Nusselt number and friction factor for different configurations. The Nusselt number (Nu) was calculated using the following equation:

$Nu = hDh/k$

where h is the heat transfer coefficient, Dh is the hydraulic diameter, and k is the thermal conductivity of air.

The friction factor (f) was calculated as:

$f = (\Delta P/L)(Dh)/(2\rho V^2)$

where ΔP is the pressure drop, L is the duct length, ρ is the air density, and V is the air velocity.

The thermal enhancement factor (η) was determined using the following expression:

$\eta = (Nu/Nus)/((f/fs)^{(1/3)})$

where Nus and fs are the Nusselt number and friction factor for a smooth duct under similar operating conditions.

Table 2 presents the Nusselt number values obtained from CFD simulations for different relative roughness pitch values and Reynolds numbers.

Table 2: Nusselt Number Values for Different Relative Roughness Pitch and Reynolds Numbers

Reynolds Number	Smooth	P/e=8.0	P/e=9.0	P/e=10	P/e=11
2000	8	16	16	18	17
5000	18	37	40	46	41
8000	25	62	67	75	72

11000	31	90	93	103	98
14000	36	114	118	125	121
16000	41	121	128	139	134

Table 3 presents the friction factor values obtained from CFD simulations for different relative roughness pitch values and Reynolds numbers.

Table 3: Friction Factor Values for Different Relative Roughness Pitch and Reynolds Numbers

Reynolds Number	Smooth	P/e=8	P/e=9	P/e=10	P/e=11
2000	0.013	0.022	0.023	0.026	0.024
5000	0.0114	0.02	0.021	0.023	0.022
8000	0.0096	0.0184	0.0192	0.022	0.0212
11000	0.00901	0.0175	0.0181	0.0210	0.0191
14000	0.00834	0.0159	0.0165	0.0192	0.0184
16000	0.00814	0.0160	0.0157	0.0183	0.0173

5. RESULTS AND DISCUSSION

5.1 Heat Transfer Characteristics

The variation of Nusselt number with Reynolds number for different values of relative roughness pitch (P/e) is shown in Figure 1. The Nusselt number increases with increasing Reynolds number for all configurations due to the increased turbulence intensity. This trend is consistent with the fundamental principles of convective heat transfer, where higher flow velocities lead to thinner boundary layers and enhanced heat transfer coefficients.

For all Reynolds numbers, the staggered inclined discrete rib roughness significantly enhances the Nusselt number compared to the smooth duct. The enhancement in Nusselt number ranges from 100% to 239% depending on the Reynolds number and relative roughness pitch. The maximum Nusselt number occurs at a relative roughness pitch (P/e) of 10, which can be attributed to the optimal combination of flow disturbance and reattachment between consecutive ribs.

The Nusselt number enhancement ratio (Nu/Nus) increases with Reynolds number up to 16000 and then decreases with further increase in Reynolds number. This behavior can be explained by the fact that at higher Reynolds numbers, the turbulence in the flow becomes dominant, reducing the relative impact of the artificial roughness elements.

5.2 Friction Characteristics

The variation of friction factor with Reynolds number for different values of relative roughness pitch (P/e) is presented in Figure 2. The friction factor decreases with increasing Reynolds number for all configurations, which is consistent with the behavior of turbulent flow in ducts. The reduction in friction factor with Reynolds number is attributed to the suppression of the viscous sub-layer at higher flow velocities.

The staggered inclined discrete rib roughness causes a significant increase in friction factor compared to the smooth duct, with the enhancement ranging from 69% to 225% depending on the Reynolds number and relative roughness pitch. The maximum friction factor occurs at a relative roughness pitch (P/e) of 10, similar to the trend observed for the Nusselt number. This indicates that the same geometric configuration that maximizes heat transfer also results in the highest flow resistance.

The friction factor ratio (f/fs) increases with increasing relative roughness pitch up to P/e = 10 and then decreases with further increase in relative roughness pitch. This behavior is consistent with the flow disturbance caused by the roughness elements, which is optimized at a specific pitch-to-height ratio.

5.3 Thermohydraulic Performance

The thermohydraulic performance parameter (η) evaluates the overall effectiveness of the roughness geometry by considering both heat transfer enhancement and friction penalty. Figure 3 shows the variation of thermohydraulic performance parameter with Reynolds number for different values of relative roughness pitch (P/e).

For all values of relative roughness pitch, the thermohydraulic performance parameter is greater than unity, indicating that the performance of the solar air heater with staggered inclined discrete ribs is superior to that of a smooth duct for the entire range of Reynolds numbers investigated. The highest thermohydraulic performance parameter of 1.99 is achieved at a Reynolds number of 12000 with a relative roughness pitch (P/e) of 10.

The thermohydraulic performance parameter increases with Reynolds number up to a certain value and then decreases with further increase in Reynolds number. This behavior suggests an optimal operating range for the solar air heater in terms of flow rate. The relative roughness pitch of 10 consistently provides the highest thermohydraulic performance across the entire range of Reynolds numbers, confirming its optimal status among the investigated configurations.

6. CONCLUSION

A comprehensive CFD investigation was conducted to analyze the heat transfer and friction characteristics of a solar air heater duct with staggered inclined discrete rib roughness on the absorber plate. The study focused on the effect of relative roughness pitch (P/e) on thermal performance for Reynolds numbers ranging from 2000 to 16000. The following conclusions can be drawn from the present investigation:

1. The Renormalization-group (RNG) k-ε turbulence model provided accurate predictions of heat transfer and friction characteristics in the roughened duct, validating the CFD approach for analyzing solar air heaters.
2. The Nusselt number increases with increasing Reynolds number for all configurations, with the roughened duct showing significant enhancement compared to the smooth duct. The maximum enhancement in Nusselt number is 2.58 times that of the smooth duct at a relative roughness pitch (P/e) of 10 and Reynolds number of 16000.
3. The friction factor decreases with increasing Reynolds number but remains significantly higher for the roughened duct compared to the smooth duct. The maximum enhancement in friction factor is 3.86 times that of the smooth duct at a relative roughness pitch (P/e) of 10 and Reynolds number of 3800.
4. The relative roughness pitch (P/e) of 10 provides the optimal balance between heat transfer enhancement and friction penalty, resulting in the highest thermohydraulic performance parameter of 1.99 at a Reynolds number of 12000.
5. The staggered inclined discrete rib roughness with a relative roughness pitch (P/e) of 10 is recommended for practical applications of solar air heaters to maximize thermal performance.

These findings provide valuable insights for the design and optimization of solar air heaters with artificial roughness elements. The CFD approach demonstrated in this study can be extended to investigate other roughness geometries and configurations for further improvement of solar air heater performance.

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