Use of a CFD Code in the Analysis of Heat Transfer Surfaces

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USE OF A CFD CODE IN THE ANALYS OF HEAT TRANSFER SURFACES

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ABSTRACT

The present paper discusses the use of a CFD code to select the cross corrugated heat transfer surface with minimum core volume of a recuperator matrix. The model comprised of three corrugated plates having their crest nearly in contact, with hot and cold fluids flow alternately through passage between the plates. Four configurations of cross-corrugated heat transfer surfaces are used for the analysis with air and argon as fluids. Design calculations of a recuperator matrix for a 10 kW micro turbine have also been carried out for the selected surfaces. The relation between the minimum core volume of the matrix from design calculation and average skin friction coefficient from CFD analysis is established to use CFD analysis for selection of heat transfer surfaces with minimum matrix core volume. Among the surfaces used for the analysis CC 2.2 -75 results in smallest core volume.

1. INTRODUCTION

An exhaust recovery recuperator is mandatory for micro turbine in order to realize a thermal efficiency of 30% or higher (McDonald,2000). Uechi *et al.* (2004) have showed that one of the most important technical issues for system efficiency is to enhance the effectiveness of the recuperator. Minimizing the recuperator size is essential for the compactness of the microturbines.Thus engineers face a challenge to design heat exchangers that can be manufactured using high volume production methods and of low cost.

The requirements such as high thermal effectiveness and low-pressure loss are to be achieved for a low cost recuperator to increase the thermal efficiency. Literature reveals that compact recuperators with cross corrugated plates are widely recommended for Micro turbines. Utriainen and Sunden (2002) conclude that the recuperator with the cross corrugated surfaces show superior performance over the others giving a small volume and weight of the heat transfer matrix, and probably is easier to manufacture with small passage dimensions.

Table 1.Geometrical data of surfaces

Surface	Pitch P (mm)	Int.Heigt Hi (mm)	P/Hi	C (m^2/m^3)	θ (Degrees)
CC 2.2 - 60	2.36	1.07	2.22	1298	60
CC 2.2 - 75	2.36	1.07	2.22	1298	75
CC 3.1 - 60	2.86	0.93	3.06	1298	60
CC 4 - 45	3.48	0.87	4.0	1299	45

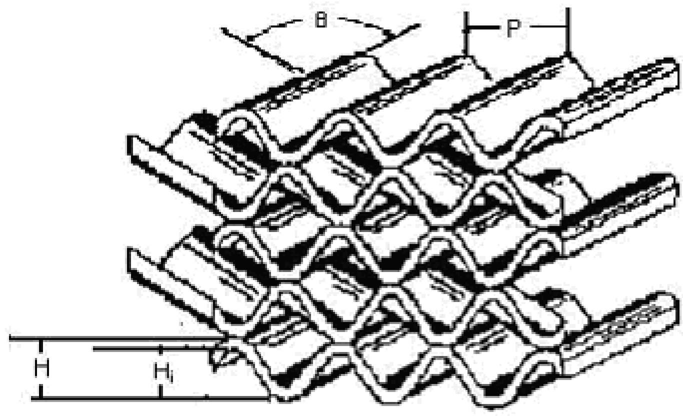

Figure 1.The cross corrugated surface

In this study the cross corrugated surfaces, CC 2.2 - 60, CC 2.2 – 75, CC 3.1 – 60, CC 4 – 45 are selected for the analysis. Design calculations of a recuperator matrix for a 10 kW micro turbine have been carried out for the selected surfaces with the assistance of experimental data's available in Utriainen and Sunden (2002). The presented results of the design calculation are focused on recuperator core. CFD analysis also is carried out for the same surfaces as an effort to establish the relation between the minimum core volume from design calculation and average skin friction coefficient from CFD analysis. The study is carried out for air and argon as heat transfer fluid which exhibit similar nature of relation between the minimum core volume from design calculation and average skin friction coefficient from CFD analysis.

The model is validated using limited experimental results available in Utriainen and Sunden (2002) and Jixiang et al.(2006), which exhibits a satisfactory agreement considering the gap between corrugated plates, indicating the validity of the present computation method.

2. DESIGN CALCULATIONS

A preferred way to compare different surfaces for a recuperator is to carry out recuperator design calculations and to compare, e.g., physical size, weight, etc. In this paper, recuperator heat transfer matrix calculations have been carried out for a representative micro turbine having an output power of 10 kW. Some selected surfaces given in Table 1.are used for the calculation. In the calculations, some assumptions, based on experience from the industry, have been made:

- 90 percent of the total heat is transferred in the heat transfer matrix.
- 60 percent of the total pressure drop is over the heat transfer matrix, All primary surface variants are suitable for the same kind of recuperator design, i.e., the pressure drop of the inlet and outlet manifolds may be regarded as equal for all surface variants.
- The metal sheet thickness is 0.08 mm.
- The hydraulic diameter is 1.54 mm for both the hot and cold sides of the recuperator matrix.

Stainless steel is selected as recuperator material since it suits our following operating condition.
Compressor pressure ratio=3
Hot gas inlet temperature=682^{o}C

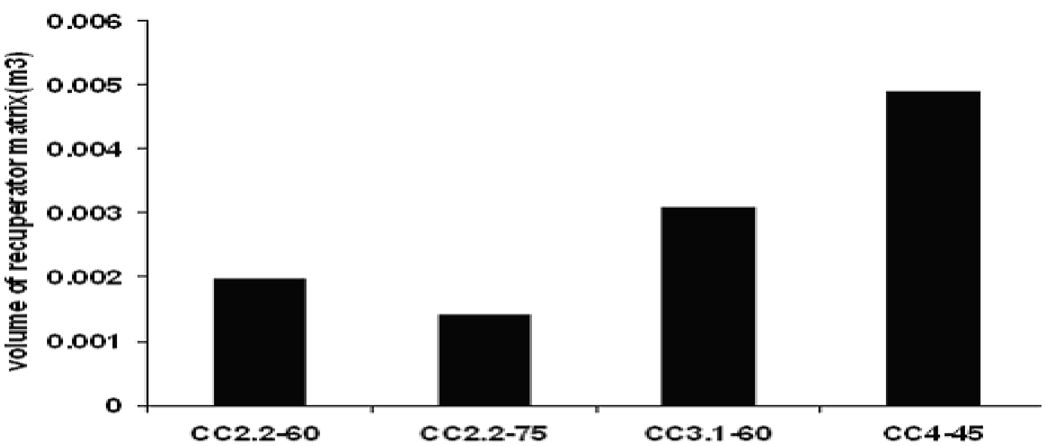

Figure 2. Results of design calculation, volume of the recuperator matrix for air

3. NUMERICAL COMPUTATION

In the present study effort is made to analyze the performances of compact heat exchanger surface comprising of corrugated walls with herringbone design, using a CFD code namely FLUENT 6.1 developed by Fluent technologies.

Decide the type of flow in such narrow passages is still an open issue in the literature. Shah and Wanniarachchi (1991) declare that, for the Reynolds number range 100-1500, there is evidence that the flow is already turbulent, a statement that is also supported by Vlasogiannis et al. (2002), whose experiments in a plate heat exchanger verify that the flow is turbulent for Re>650. Lioumbas et al.(2002), who studied experimentally the flow in narrow passages during counter-current gas-liquid flow, suggest that the flow exhibits the basic features of turbulent flow even for the relatively low gas Reynolds numbers tested (500<Re<1200). Focke and Knibbe(1986) performed flow visualization experiments in narrow passages with corrugated walls. They concluded that the flow patterns in such geometries are complex, due to the existence of secondary swirling motions along the furrows of their test section and suggest that the local flow structure controls the heat transfer process in such narrow passage.

Table 2. Geometric parameters used for the model

Plate length	0.062m
Plate width	0.010m
Distance between the crest	0.0001m

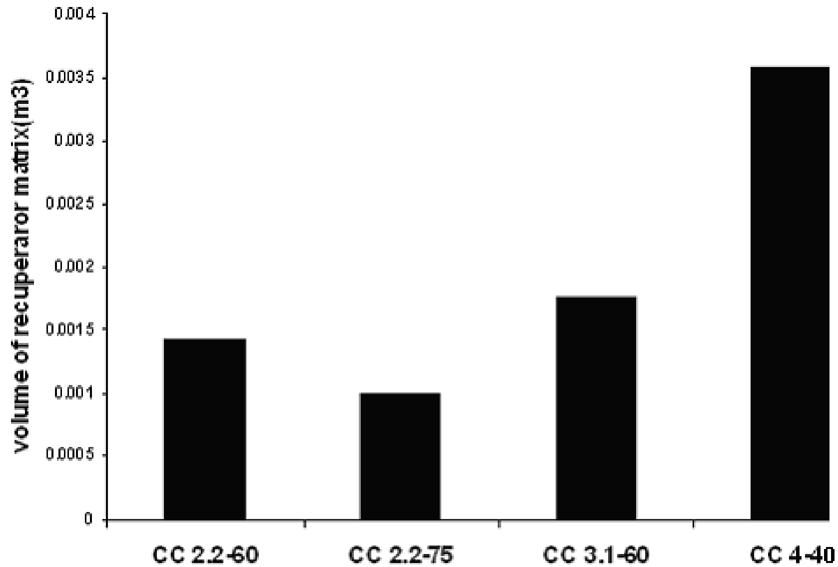

Figure 3. Results of design calculation, volume of the recuperator matrix for argon

The choice of the most appropriate turbulence model for CFD simulation is another open issue in the literature. The most common two-equation model, based on the equations for the turbulence energy k and its dissipation ε, is the k–ε model. Ciofalo et al. (1996) state that the standard k–ε model using 'wall functions' over predicts both wall shear stress and wall heat flux, especially for the lower range of the Reynolds number encountered in this kind of equipment. Menter and Esch (2001) note that the over prediction of heat transfer is caused by the over prediction of turbulent length scale in the region of flow reattachment, which is a characteristic phenomenon appearing on the corrugated surfaces in these geometries. An alternative to the k–ε model is the k–ω model developed by Wilcox. The k–ω model, which uses the turbulence frequency ω in place of turbulence dissipation ε, appears to be more robust,

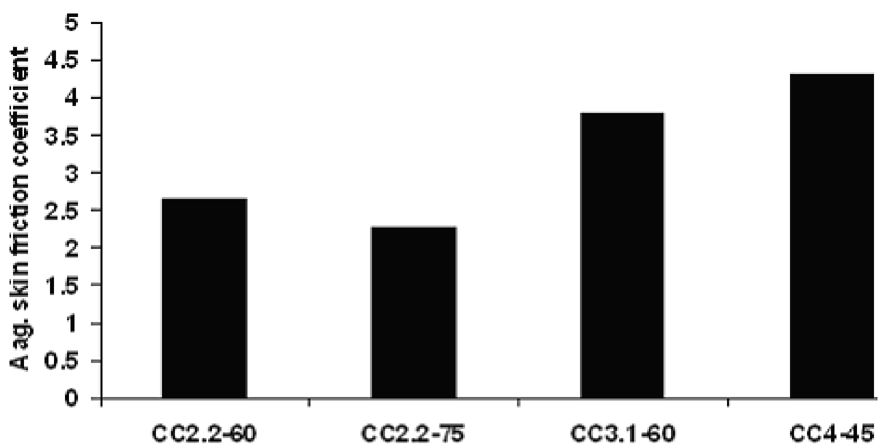

Figure 4. Results of CFD analysis, average skin friction coefficient for air

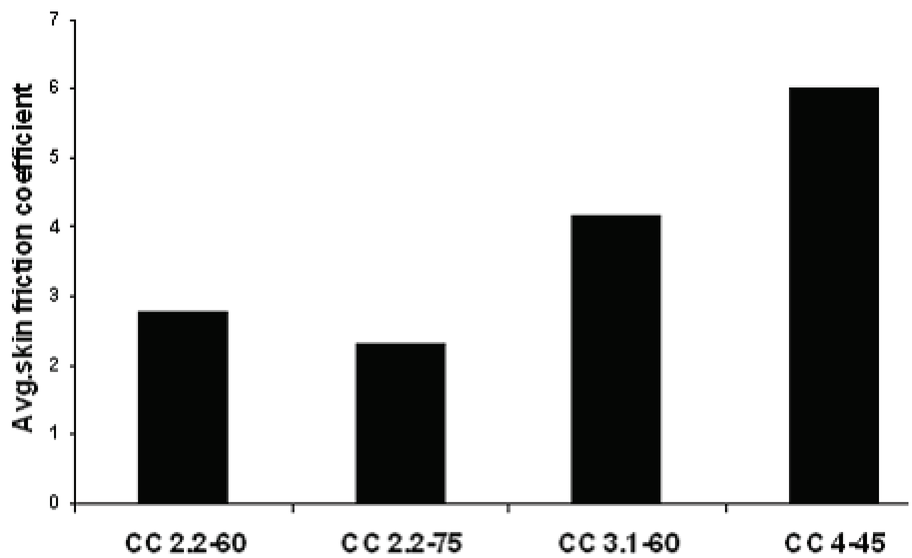

Figure 5. Results of CFD analysis, average skin friction coefficient for argon

even for complex applications, and does not require very fine grid near the wall. The main disadvantage of k–ω model is its sensitivity to the free stream values of turbulence frequency ω outside the boundary layer, which affects the solution and, in order to avoid this, a combination of the two models, k–ε and k–ω, i.e., the SST (Shear-Stress Transport) model is proposed (Menter and Esch (2001)). The SST model can switch automatically between the two aforementioned turbulence models using specific 'blending functions' that activate the k–ω model near the wall and the k–ε model for the rest of the flow. Although the SST model combines the most widely used two-equation turbulence-models, other models, like LES (Large-Eddy Simulation) is considered more appropriate in turbulent flow simulation. However, the LES model is considered less robust and requires high-computational power.

In the present study the SST turbulence model is preferred over other flow models for simulations. This simple model, comprised of three corrugated plates having their crest nearly in contact, with hot and cold fluids flow alternately through passage created between the plates. Geometric parameters used for the model is given in Table 2. Analysis is carried out for air and argon as heat transfer fluid. Mass flow rate at inlet and pressure at outlet is used as the boundary condition. Same mass flow rate at inlet is applied for all the surfaces.

4. RESULTS AND DISCUSSION

The design calculation results and CFD analysis is compared with bar chart for volume of the recuperator matrix and average skin friction coefficients for the selected cross corrugated heat transfer surfaces. The first one is the bar chart for volume of the recuperator matrix, see Fig. 2 and Fig.3, where the vertical axis represents the design calculation result of recuperator matrix volume. The second plot is the bar chart for average skin friction coefficients, see Fig.4 and Fig.5, where the vertical axis represents the CFD analysis result for average skin friction coefficients. The plots in Fig.2 and Fig.4, Fig.3 and Fig 5 , indicates the relation between the results of design calculation for minimum core volume and results of CFD analysis for average skin friction coefficient. The surface with least recuperator matrix core volume is also seems to be with least average skin friction coefficient for separating wall. The increase of average skin friction coefficient indicates the requirement of increased core volume of the recuperator matrix. The authors carried out studies for air and argon as heat transfer fluids which exhibit similar nature of relation between the minimum core volume from design calculation and average skin friction coefficient from CFD analysis.

5. PERFORMANCE PARAMETERS AND MODEL VALIDATION

In heat exchanger design, the most relevant performance parameters are pressure drop and heat transfer rate. It is desirable that high heat transfer rates are obtained while pressure losses are as low as possible. The pressure losses are evaluated using dimensionless pressure gradient per unit length along the mainstream direction.

To the best of author's knowledge, experimental values of heat transfer and pressure drop are very limited in the open literature for the corrugated plate geometry, since these data are proprietary. The reported study by Stasiek (1998) provided no detailed data about the CC geometry studied. The present study confirms the validation of numerical code by comparing the numerical results predicted with the experimental results presented by Utriainen & Sunden (2002) and method used for comparison by Jixiang et al. (2006) for CC2.2-75 geometry. Fig.6 and Fig.7 illustrate the friction factor and Nusselt number variation with Reynolds number from CFD analysis and experimental results presented by Utriainen & Sunden (2002).In spite of difference in geometry (the gap between the crest of two alternate plates used in the CFD analysis) simulation results are in satisfactorily good agreement with the experimental results available, indicating the validity of the present computation method.

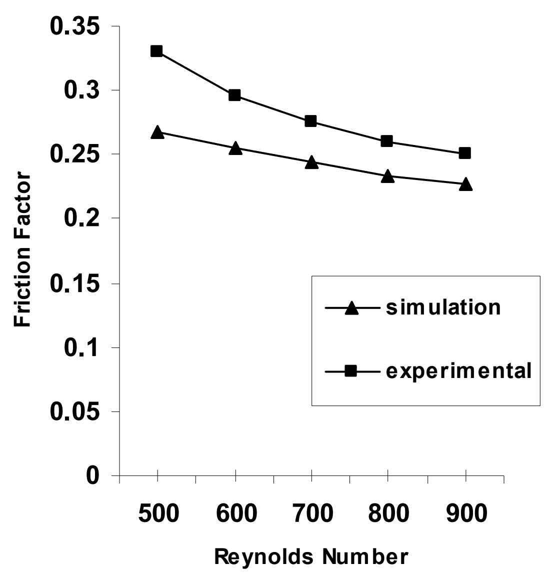

Figure 6. Comparison between predicted and experimental results for fanning friction factor for CC2.2-75 surface and air is the fluid.

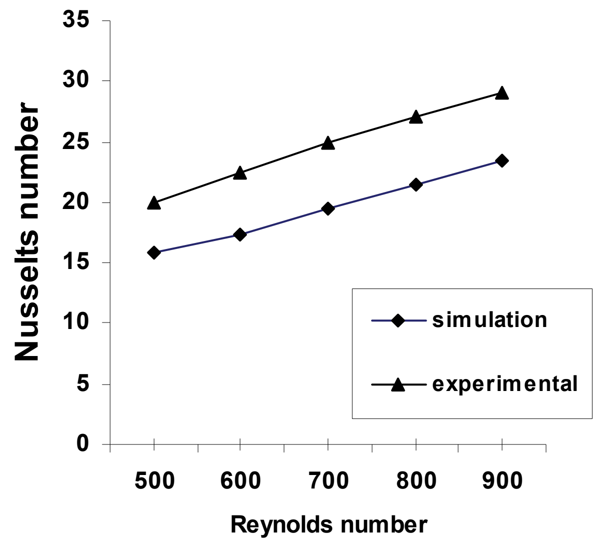

Figure 7. Comparison between predicted and experimental results for average Nusselt number for CC2.2-75 surface and air is the fluid.

6. SUMMARY AND CONCLUSIONS

The variation of main geometric details of cross corrugated surfaces (i.e. aspect ratio and angle of corrugation) makes it increasingly difficult to have a general design method. In the absence of adequate 'database' covering all possible configurations, it is nearly impossible to predict the highly effective configuration. Thus CFD simulation is effective, as it allows computation for various geometries, and study of the effect of various design configurations on heat transfer and flow characteristics.

The results of design calculation carried out on recuperator matrix of different surfaces indicate that recuperator matrix core volume vary directly with aspect ratio and inversely with the corrugation angle. Among the surfaces used for the design calculations CC 2.2 -75 requires least core volume for the specified condition.

The results of CFD analysis show the direct variation of aspect ratio and heat transfer coefficient and inverse variation of corrugation angle and heat transfer coefficient for a given size and given input flow variables. The surface CC4-45 is most effective among the surface analyzed in CFD analysis for same size and same input flow variables.

The results of CFD analysis for average skin friction coefficients can be used to compare with the results of design calculations for minimum recuperator matrix volume. The cross corrugated surface with the minimum recuperator matrix volume (i.e CC 2.2 -75) is also one with the minimum average skin friction coefficient for the separating wall. Thus CFD analysis can be used to narrow down our studies on heat transfer surfaces for minimum core volume of recuperator matrix.

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