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Hydraulic and thermal performances of a novel configuration of high temperature ceramic plate-fin heat exchanger

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HIGHLIGHTS

- Rip saw fin design (case 9) was considered to be the best because it has thin fins and has higher heat transfer coefficient.
- Due to higher surface area density the heat transfer coefficient and Nusselt number obtained for case 7 is lower than other fin types.
- The values of the average Nusselt number obtained for all the cases vary in small order of magnitude.
- The maximum Nusselt number was obtained for the ripsaw fin design (case 9).

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ABSTRACT

A novel fin configuration for high temperature ceramic plate-fin heat exchanger (PFHE) was developed using the three-dimensional computational fluid dynamics (CFD) FLUENT code. Numerical analysis was carried out for different types of fins and their results were compared with the selected design. The working fluids used in the model were sulfur trioxide, sulfur dioxide, oxygen and water vapor. Fluid flow, heat transfer, pressure drop and properties like Nusselt number, friction factor and *j*-factor were studied for various fin configurations. The rip saw fin design (case 9) with thickness of 0.05 mm gives the maximum heat transfer performance with less pressure drop and friction factor. The numerical result was compared with the analytical result for rectangular fins and they were found to be in reasonable agreement. In addition to it, the results from the selected ripsaw design were compared with the result from the model with no fins (case 1). It was found that thermal enhancement factor of 2.3211 and average Nusselt number of 4.215 was obtained for the selected design. The results of the rip saw fin design were found in good agreement with the analytical results of a rectangular fin. Further effects of Reynolds number on pressure drop and Nusselt number were studied.

1. Introduction

For decades, efforts have been undertaken to produce more efficient heat exchangers for variety of applications. The need for lightweight, space saving and economical heat exchangers has driven to the development of compact surfaces. compact heat exchangers (CHE) are widely in demand due to their improved effectiveness, smaller volume, higher surface area density and power savings. Surface area density greater than 700 m^2/m^3 is achieved by incorporating fins, ribs, etc. [1] The widely used plate-fin heat exchanger has a variety of augmented surfaces such as plain fins, wavy fins, offset strip fins, perforated fins, pin fins and louvered fins [2]. A plate-fin heat exchanger is a form of compact heat exchanger made of block of alternating layers of corrugated fins separated by parting sheets. High degree of surface compactness and the periodic starting and development of laminar boundary layers near the fins enhances heat transfer in these heat exchangers.

The thermal–hydraulic performances of such heat exchangers are strongly influenced by their geometry and flow configurations. From the research done by Kayansayan [3] the effect of performance of the plate fin-tube cross flow heat exchangers due to the outer surface geometry was considered. Around 10 geometrical configurations were tested and the Reynolds number was varied from 200 to 30,000. It was found that the heat transfer coefficients strongly depend on the finning factor ε. As the value of ε increases the *j*-factor decreases. Sheik Ismail et al. [4] studied three typical compact plate-fin heat exchangers using FLUENT software for quantification of flow maldistribution effects with ideal and real cases. Fernandez-Seara et al. [5] carried out the experimental analysis of a titanium brazed plate-fin heat exchanger with offset strip-fins in liquid–liquid heat transfer process. Pressure drop and heat transfer characteristics were determined and the Wilson plot

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Nomenclature

C_p	specific heat constant pressure, J kg^{-1} K^{-1}
D_h	hydraulic diameter, m
G	mass velocity, kg/s m^{-2}
k	thermal conductivity of the fluid, W m^{-1} k^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
p	static pressure, Pa
q	heat flux, W m^{-2}
R	gas constant, J K^{-1} mol^{-1}
Re	Reynolds number
j	Colburn factor
f	friction factor
t	thickness of the fins
T	temperature, K
α	aspect ratio
$\overline{Nu}$	average Nusselt number
U	mean velocity component (i = 1, 2, 3), m s^{-1}
Greek	
v	volumetric flow rate, ml min^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
λ	fin length
ρ	density, kg m^{-3}
ΔP	pressure drop, Pa
Subscripts	
b	average value
w	wall
i	inlet
o	outlet

method was used for the reduction of the experimental heat transfer data. It was found that the experimental results agree well with the correlation equation obtained from the Wilson plot technique.

Ranganayakaulu and Seetharamu [6] carried out an analysis of a cross-flow compact plate-fin heat exchanger for the combined effects of two-dimensional longitudinal heat conduction through the exchanger wall, flow non-uniformity and temperature distribution was carried out using finite element method. The exchanger effectiveness and its deterioration due to these effects were studied for various designs and operating conditions. Dubrovsky [7] carried out an experimental investigation of a new convective rational heat transfer augmentation law in plate-fin heat exchanger. The results indicated that the fundamental character and causes limiting rational heat transfer augmentation depend upon the heat transfer surface corrugation.

In the study carried out by Yakut et al. [8] the effects of heights and widths of the hexagonal fins, streamwise and spanwise distances between fins and flow velocity on the heat and pressure drop characteristics were investigated using the Taguchi experimental design-method. From the results it was found that the heat transfer results were mostly influenced by the fin height, fluid velocity and fin width. The fin width was found to be the most effective parameter on friction factor. Naik and Probert [9] investigated the steady state rate of heat transfer from an array of rectangular uniform duralumin fins constructed with various inter-fin spacings, heights and lengths. It was found that increasing fin height increases heat transfer rates from the fin arrays and decreasing the length of the fins resulted in lower steady-state rates of dissipation per unit base area.

Lot of research has been carried out on offset strip fin heat exchangers. Manglik and Bergles [10] studied the heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger. The f and j parameters were also found for laminar, transition and turbulent flow regimes. Steady state three-dimensional numerical model was used to study the heat transfer and pressure drop characteristics of an offset strip fin heat exchanger by Bhowmik and Lee [11]. In this paper, f and j factor correlations have been used to analyze fluid flow and heat transfer characteristics of offset strip fins in the laminar, transition and turbulent flow regions.

High temperature heat exchangers are the key conversion components for the thermally driven hydrogen production process. The research carried out by Ma et al. [12] shows the effect of inlet temperature and rib height on the fluid flow and heat transfer in the ribbed channel in the high temperature heat exchanger. From the results it was found that the Nusselt number and the friction factor are unsuitable to compare heat transfer and pressure drop performance among different temperature conditions. Numerical analysis on novel bayonet high temperature heat exchanger with inner and outer fins and the investigation of the stress analysis of internally finned bayonet tube in high temperature heat exchanger using ANSYS were carried out by Ma et al. [13,14].

Ponyavin et al. [15] carried out a numerical analysis on the three-dimensional computational model of the ceramic high-temperature heat exchanger to investigate fluid flow, heat transfer, chemical reaction and stress analysis within the decomposer. A decomposition rate of 0.515% was achieved for SO_3 using this design. In the work done by Schulte-Fischedick et al. [16] ceramic plate-fin heat exchanger based on the offset strip-fin design for externally fired combined cycle was presented.

However, few analyses have been carried out on the ceramic plate-fin heat exchanger for the production of hydrogen. The study on the numerical analysis of ceramic PFHE was carried out to investigate the pressure drop and heat transfer performance for different fin designs at high temperatures. A microchannel model of the ceramic PFHE was studied in order to save computer memory and computational time. The main operating parameters for the heat exchanger design models for the current study were taken from the research done by Ponyavin et al. [15].

2. Physical model and description

Nine typical PFHE design configurations used for three-dimensional computational fluid dynamics (CFD) simulations were modeled in Solidworks. One cold plate and one hot plate are stacked alternatively and this arrangement is called single-banking configuration. The geometry and the dimensions of the heat exchanger used in the current study were obtained from the model by Ponyavin et al. [15]. According to their study the geometry of the heat exchanger was designed according to the process design proposed by General Atomics (GA). In the study by Ponyavin et al. [15] hot fluid (helium) flows through the entire channel and cold fluid (reacting fluid) with fins occupies three-fourth of the channel whereas in the current study both the hot and cold fluids flow through the entire channel. The dimensions used by Ponyavin et al. [15] and the current study are shown in Table 1. In the Ponyanin et al. [15] model there were three channels for hot fluid, reacting fluid, recuperating fluid and three solid regions. The current study has hot fluid channel, cold fluid channel and two solid regions. The recuperating