Energy Conversion and Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimization of inlet part of a microchannel ceramic heat exchanger using surrogate model coupled with genetic algorithm ☆

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Optimization
Microchannel ceramic heat exchanger
Surrogate model
Radial basis neural network
Genetic algorithm
Flow uniformity

ABSTRACT

High temperature resistance and corrosion resistance make ceramic materials available for heat exchangers operating under high temperature or harsh chemical conditions. And the importance of the effect of flow maldistribution on thermal-hydraulic performance of heat exchangers has been demonstrated by a lot of researches. In this work, the nonuniformity of fluid flow is focused on to improve the performance of a microchannel ceramic heat exchanger. The inlet part of a microchannel ceramic heat exchanger is optimized using surrogate model coupled with genetic algorithm. Specifically, 30 sample points are designed by Latin hypercube sampling method and calculated by computational fluid dynamics. Radial basis neural network is established with the sample data and employed to predict the specific fluid flow distribution within design space as a surrogate model. Specifically, the surrogate model predicts the specific flow distribution instead of a single target value of nonuniformity in previous surrogate model. The results indicate that such a method has a significant advantage over the previous surrogate model. The genetic algorithm is implemented to search for the optimal point. The nonuniformity of fluid flow is reduced by 68.2% and pressure drop is increased by 6.6% by the optimization, which means the uniformity of fluid flow in the heat exchanger is improved significantly with just a little cost of pressure drop.

1. Introduction

Ceramic materials have advantages over metal materials for high temperature resistance and corrosion resistance. So it is available for ceramics to operate under high temperature or harsh chemical conditions. With the development of micro-scale manufacture technology, the ceramic microchannel heat exchangers have been widely used in several advanced energy transport systems instead of conventional heat exchangers. Many studies have been performed on ceramic heat exchangers. Sommers et al. [1] reviewed numerous applications of ceramic heat exchangers, including the use for liquid-to-liquid heat exchangers, liquid-to-gas heat exchangers, gas-to-gas heat exchangers, and heat sinks. Potential applications of ceramic heat exchangers also have been introduced such as primary heat exchangers in gas-fired furnaces for space heating, high temperature recuperators and chemical digesters and open-cell foams for reactive heat exchange processes and filtration, which reflected the current state of the art of ceramic materials for use in a variety of heat transfer systems. Schulte-Fischedick et al. [2] presented a ceramic plate-fin heat exchanger based on the offset strip fin (OSF) design, which can be used as the high temperature heat exchanger in the externally fired combined cycle (EFCC) or other applications that need operational material temperatures up to 1250 °C. A process consisting of six steps has been introduced to apply the environmental barrier coating (EBC) to all parts that have contact with aggressive flue gases. Alm et al. [3] manufactured and test the heat transfer performance of three ceramic micro heat exchangers including counterflow and crossflow modes. Low-pressure injection molding (LPIM) has been used for shape manufacturing of ceramic micro-components. Takeuchi et al. [4] performed a numerical study to investigate the heat transfer performance of a silicon-carbide (SiC) compact heat exchanger, which was proved helpful for the use of HTTR and VHTR nuclear reactors by experimental results. Kee et al. [5] designed, evaluated and manufactured an all-ceramic compact counterflow microchannel heat exchanger, which had an overall footprint of 50 mm by 100 mm, as shown in Fig. 1. Numerical analysis has been conducted to finish the design process. A new fabrication process called Pressure Laminated Integrated Structures (PLIS) was employed to reduce the cost.

☆ *Presented at the 11th SDEWES Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES2016), September 4- September 9, 2016 in Lisbon, Portugal* (Original paper title: "Optimization of inlet part of a microchannel ceramic heat exchanger using surrogate model coupled with genetic algorithm (GA)" and Paper No.: # SDEWES2016-0083).

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http://dx.doi.org/10.1016/j.enconman.2017.04.035
0196-8904/

Nomenclature

A_c	flow cross-sectional area of microchannel, m^2
D_h	hydraulic diameter, m
k	turbulence kinetic energy, m^2/s^2
f_1	objective function for nonuniformity
f_2	objective function for pressure drop, Pa
Δp	pressure drop in microchannel, Pa
P	channel-wetted perimeter, m
Q_i	mass flow rate of i_{th} channel of the first group of ribs, kg/s
Q_{avg}	average mass flow rate of five channels of the first group, kg/s
S	source term in governing equation
S_i	ratio of Q_i and Q_{avg}
u	velocity components in x directions, m/s
v	velocity components in y directions, m/s
w	velocity components in z directions, m/s
x_i	design variables for the location of the channels of the first group, mm

Greek

ε	rate of dissipation of turbulent kinetic energy, m^2/s^3
η_t	turbulent viscosity coefficient, Pa·s
η	viscosity coefficient, Pa·s
η_{eff}	effective viscosity coefficient, Pa·s
Γ	generalized diffusion term in governing equation

Subscripts

ave	average
eff	effective
t	turbulent

Actually, fluid flow maldistribution is a common problem for multichannel heat exchangers, including ceramic microchannel heat exchangers. Many studies on the flow maldistribution problem of multichannel heat exchangers have been performed. The previous researches indicated that the flow maldistribution has significant effect on thermal-hydraulic performance of heat exchangers. By theoretical analysis, Fleming [6] studied the effect of flow maldistribution on the heat transfer performance of the multichannel heat exchangers under different NTU (number of transfer unit) numbers. The results indicated that the heat transfer performance would deteriorate significantly due to the fluid flow maldistribution, especially in high NTU case. Pasquier et al. [7] optimized the header of a printed circuit heat exchanger for better flow uniformity, the improvement of heat transfer performance is up to 24% under the optimized design with good flow uniformity. Mao et al. [8] studied the impact of airflow maldistribution in cross-flow condenser with multilouvered fin and flat tube heat exchangers by the model based on finite volume method. The results demonstrated the reduction of heat transfer rate with the maldistribution of airflow. Ranganayakulu et al. [9] studied the effects of two-dimensional flow maldistribution at inlet on both hot and cold sides of a crossflow plate-fin compact heat exchanger by using a finite element method. A mathematical equation was developed to generate different types of fluid flow maldistribution models considering the possible deviations in fluid flow. The results indicated that the thermal performance deteriorations and variation in pressure drops were quite significant in some typical applications due to the fluid flow nonuniformity. Zhang [10] investigated the flow maldistribution of a cross-flow air to air heat exchanger and its effect on the thermal performance. The results indicated that if the channel pitch is larger than 2 mm, a 10–20% heat transfer deterioration could occur since the maldistribution is quite large. The results also showed that it is required to couple the inlet part, the outlet part, and the core of heat exchanger to clarify flow maldistribution problems. Yaïci et al. [11] conducted three-dimensional computational fluid dynamics (CFD) simulations to study the effect of inlet air flow maldistribution on the thermo-hydraulic performance of plate-fin-and-tube laminar heat exchangers. The results confirmed that the influence of inlet fluid flow nonuniformity is of great importance for the thermo-hydraulic performance of heat exchangers.

Meanwhile, related numerical and experimental studies on the evaluation of flow maldistribution were conducted and several methods for improving the flow uniformity were proposed. Habib et al. [12] conducted an evaluation of flow maldistribution in air-cooled heat exchangers by using a 3-D computational method. The effects of several influencing factors on flow maldistribution were also studied, including the number of nozzles, nozzle location, nozzle geometry, nozzle diameter, inlet flow velocity. Wen and Li [13] proposed an improved inlet header configuration which consists of a baffle with small holes. The numerical results indicated that the improved configuration could effectively improve the fluid flow uniformity of the plate-fin heat exchanger. Wen et al. [14] also investigated the flow maldistribution of entrance configuration in a plate-fin heat exchanger by means of particle image velocimetry (PIV). The experimental results revealed that conventional entrance configuration showed serious problem of flow maldistribution, and the punched baffle could effectively improve the fluid flow uniformity. Chu et al. [15] numerically studied the maldistribution of fluid flow at the inlet manifold of a high temperature multi-channel compact heat exchanger and proposed four modified inlet manifolds with the application of inclined baffle, segmental baffle, helical baffle and improved helical baffle, which could reduce the nonuniformity of the flow. According to the CFD results, the Nusselt number could be increased by 24% averagely due to the produced spiral fluid flow with acceptable pressure drop. Said et al. [16] presented two approaches to reduce the flow maldistribution in a heat exchanger with header-tube arrangement. The first approach was the introduction of an orifice at the actual tube inlet and the second approach was the introduction of an nozzle at the actual tube inlet. The flow maldistitribution was evaluated by the standard deviation in the normalized mass flow rate of the channels. The results indicated that by using orifice approach, flow maldistribution could be reduced by approximately 12 times the original. However, the pressure drop would increase by 7.8%. By using the nozzle approach, the flow maldistribution could be reduced by approximately 7.5 times the original one, while the pressure drop would decrease by 9.8%. Pasquier et al. [7] conducted CFD simulations and optimization of fluid flow distribution inside printed circuit heat exchanger headers. Four kinds of inlet headers were compared. By optimization, a novel core integrated header with seven merged channels was proposed. The flow nonuniformity of the heat exchanger with this novel inlet and outlet headers is reduced by 91%, but the pressure drop is increased by 114% compared with the baseline configuration, whereas it shows the best heat transfer performance as well due to the improvement of flow uniformity.

At present, the optimization technique combined with numerical or experimental study has been widely employed in the field of thermal management and optimization in different energy conversion systems. Hsieh et al. [17] conducted optimization to minimize heat concentrations of high-power light-emitting diode (LED)