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Optimization design of shell-and-tube heat exchanger by entropy generation minimization and genetic algorithm

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ABSTRACT

In the present work, a new shell-and-tube heat exchanger optimization design approach is developed, wherein the dimensionless entropy generation rate obtained by scaling the entropy generation on the ratio of the heat transfer rate to the inlet temperature of cold fluid is employed as the objective function, some geometrical parameters of the shell-and-tube heat exchanger are taken as the design variables and the genetic algorithm is applied to solve the associated optimization problem. It is shown that for the case that the heat duty is given, not only can the optimization design increase the heat exchanger effectiveness significantly, but also decrease the pumping power dramatically. In the case that the heat transfer area is fixed, the benefit from the increase of the heat exchanger effectiveness is much more than the increasing cost of the pumping power.

1. Introduction

Energy conservation is vital for the development of world economy. To use energy more efficiently is one of important measures for saving energy. Heat exchangers are used to transfer thermal energy between two or more media and widely applied to power engineering, petroleum refineries, chemical industries, food industries and so on. The shell-and-tube heat exchanger (STHE) shown in Fig. 1 is the most common heat exchanger type. Therefore the study of its optimization design is of great importance for conserving energy in heat exchange processes.

The available objective functions for heat exchanger optimization designs may be classified into two groups, one is based on the first law of thermodynamics and another is based on the combination of the first and second law of thermodynamics. In recent decades the second group has aroused widespread interest, which includes the entropy and exergy. Based on the concept of entropy, several heat exchanger performance criteria were developed; these criteria have their own characteristics and constraints, but also are interrelated as described in [1]. Among them the entropy generation number is the most frequently applied one proposed by Bejan [2–4], and entropy generation minimization (EGM) has been widely applied to the optimization design of heat exchangers.

Bejan [3] demonstrated that EGM may be used by itself in the preliminary stages of design, in order to identify trends and the existence of optimization opportunities. Vargas et al. [5] presented an approach to determine the internal geometric configuration of a tube bank by optimizing the global performance of the installation that uses the cross flow heat exchanger. Based on the EGM, Oğulatu et al. [6] analytically carried out an optimization design of a cross flow plate heat exchanger, and examined the optimum result by the experimental data.

From our knowledge the applications related to the EGM are mainly based on the dimensionless entropy generation defined by scaling the entropy generation rate on the heat capacity rate. However it was found that the entropy generation number (EGN) defined in such a manner exhibits the so-called 'entropy generation paradox' [7,8]. In order to avoid this paradox the ratio of heat transfer rate to the cold fluid inlet temperature can be employed to non-dimensionalise the entropy generation rate [7]. The obtained dimensionless entropy generation number is called as the modified entropy generation number in the following discussion and employed as the objective function in our heat exchanger optimization design approach.

Usually the heat exchanger optimization design with multiple design variables is more practicable, and its global optimum solution is more desirable. The genetic algorithm is a powerful tool to address the multi-variable optimization problems. Recently the application of genetic algorithm on thermal engineering has received much attention [9–11].

In the present work, we attempt to put the entropy generation minimization and genetic algorithm into the STHE optimization design practice. In this method the modified entropy number is defined as the objective function, the Bell–Delaware design method for the STHE is utilized, the multiple design variables are assumed and the genetic algorithm is used to solve the resulting optimization problems. The influence of the selected design variables and

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Nomenclature

A_o	heat exchange area (m^2)
Bs	the ratio of the baffle spacing to shell diameter
c_p	specific heat (J/kg K)
C_{ER}	cost of energy recovery (€/kW h)
C_E	energy cost (€/kW h)
C^*	heat capacity rate ratio
d	tube diameter (m)
D_s	shell inside diameter (m)
f_i	fanning friction coefficient
G	mass flow velocity (kg/m^2 s)
H	annual operating time (h/yr)
j_o	heat transfer factor
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
n	the number of tubes
N_b	the number of baffles
N_c	number of effective tube rows in one cross flow section
N_{cw}	number of effective tube rows crossed in the baffle window
N_s	Bejan's entropy generation number
N_{s1}	modified entropy generation number
Ntu	number of heat transfer units
Pr	Prandtl number
Q	actual heat transfer rate (W)
Q_{max}	maximum possible heat transfer (W)
r	fouling resistances (m^2 K/W)
R_b	the correction factor for bypass flow
R_1	the correction factor for baffle leakage
R_s	the correction factor for unequal baffle spacing at inlet and/or outlet
s	tube pitch (m)
$\dot{S}_{gen}$	entropy generation rate (W/K)
T	temperature (K)
U	heat transfer coefficient (W/m^2 K)
w	tube side flow velocity (m/s)
$\dot{W}$	overall pumping power (kW)

Greek symbols

ΔC_O	increased annual operating cost (€/yr)
ΔC_S	additional annual benefit from recycling (€/yr)
ΔP	pressure drop (Pa)
ΔP_{bk}	pressure drop for an ideal cross flow section (Pa)
ΔP_{wk}	pressure drop for the ideal window section (Pa)
δ	tube wall thickness (m)
ε	heat exchanger effectiveness
η	overall pumping efficiency
θ	central angle of baffle cut (rad)
λ	thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^2)

Subscripts

1	hot fluid
2	cold fluid
i	inside
o	outside
s	shell side
t	tube side
w	tube wall

Superscripts

i	inlet
o	outlet

other parameters on the entropy generation is explored by analyzing the optimization results.

2. Optimization design method

2.1. Genetic algorithm

The basic principle of genetic algorithm was first proposed in the 1970s by John Holland. The genetic algorithm is based on the natural selection, which was found in biological evolution process. In the optimization design application, before a genetic algorithm can be put to work, a method is needed to encode potential solutions to the optimization problem in a form that a computer can process. One common approach is to encode solutions as binary strings: sequences of 1's and 0's, where the digit at each position represents the value of some aspect of the solution. A metric called a fitness function that allows each potential solution (individual) to be quantitatively evaluated. After a random initial population in the ranges of design variables is generated, the algorithm creates a sequence of new generations iteratively until the stopping criterion is met. In this process, the selection of parents is based on their fitness; children (next generation or population) are produced by making random changes to a single parent (mutation) or by combining the vector entries of a pair of parents (crossover),

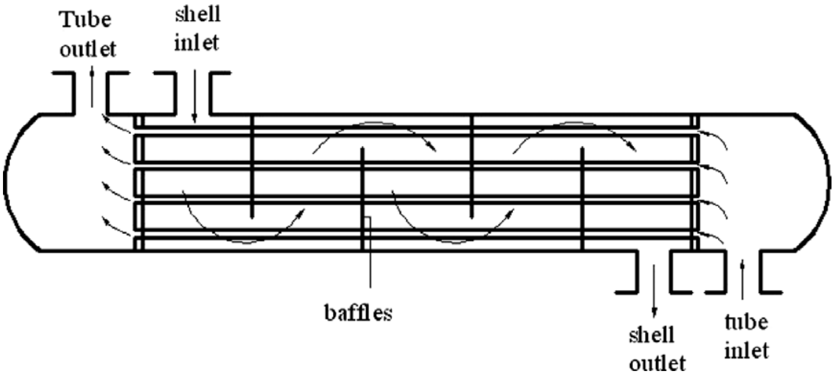

Fig. 1. Diagram of a typical STHE.