Available online at www.sciencedirect.com
ScienceDirect
Energy Conversion and Management 48 (2007) 2399–2406
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

The effect of fouling on thermodynamic performance of forced convective heat transfer through a duct

Shuang-Ying Wu *, Yan Chen, You-Rong Li, Dan-Ling Zeng

College of Power Engineering, Chongqing University, Chongqing 400044, PR China

Received 11 January 2006; received in revised form 23 July 2006; accepted 6 March 2007
Available online 24 April 2007

Abstract

Based on the first and second thermodynamic laws, a new systematic approach to study in detail the effect of fouling on the thermodynamic performance of forced convective heat transfer through a duct with constant wall temperature and constant wall heat flux for thermally and hydrodynamically fully developed turbulent flow is investigated. When considering fouling exists inside the duct, the local and mean exergy variation coefficient, exergy variation flux, dimensionless exergy variation number and the equation of exergy variation rate of working fluids, etc. have been put forward and their generalized expressions derived. A criterion evaluating the effect of fouling on the exergy variation of working fluids of the forced convective heat transfer process, which is defined as the exergy variation degradation rate, has been put forward. By reference to a duct, the numerical results of the exergy variation of working fluids are obtained (considering fouling or not), the effects of Reynolds number, the thickness of the fouling layer, dimensionless inlet temperature difference and wall heat flux on the exergy variation of working fluids are discussed. The results show that the exergy variation degradation rate increases with the increase of Reynolds number and decreases with the increase of dimensionless inlet temperature and wall heat flux. The exergy variation caused by the heat conduction of fouling plays an important role in the total exergy variation of working fluids.

Keywords: Convective heat transfer; Exergy; Fouling

1. Introduction

Heat exchangers are extensively used in the power and process industries to transfer heat from one fluid to another, and they are fouled to a greater or lesser extent. Fouling is known to have an adverse effect on heat transfer by increasing the heat transfer resistance.

As the fouling layer starts growing, the heat transfer decreases due to the low thermal conductivity of the fouling layer. At the same time, the flow passage cross sectional area decreases, and the frictional pressure drop increases. These two phenomena give rise to a variation in the irreversibilities caused by the heat transfer and viscous flow processes. It is important to mention that designers and operators of heat transfer equipment must be able to predict performance variation as the fouling proceeds. Until now, the methods employed in predicting the effect of fouling on the heat transfer performance mainly are fouling coefficient method, cleaning coefficient method, excess area method, etc. [1].

Convective heat transfer appears widely in many heat exchange equipments. Efficient utilization of energy is the primary objective in the design of a thermodynamic system. Second law analysis is the gateway for optimization in thermal equipments and systems. Entropy generation or exergy destruction due to heat transfer and fluid flow through a duct has been investigated by many researchers, and a non-dimensional entropy generation number is always employed in the irreversibility examination of convective heat transfer. A study of entropy generation in the fundamental convective heat transfer process was conducted by Bejan [2]. He demonstrated the spatial

* Corresponding author. Tel.: +86 23 65112284; fax: +86 23 65102473.
E-mail address: shuangyingwu@yahoo.com.cn (S.-Y. Wu).

0196-8904/$ - see front matter
doi:10.1016/j.enconman.2007.03.004

Nomenclature

A	area, m^2
c_p	specific heat capacity at constant pressure, J/kg K
d_i	inner diameter of duct, m
e	exergy flux, W/m^2
e_x	local exergy flux, W/m^2
e'	specific exergy, J/kg
e^*	dimensionless exergy variation flux
E	exergy variation rate, W
E^*	dimensionless exergy variation rate
f	friction factor
G	mass rate, $G = \rho u_m(\pi d_i^2/4)$, kg/s
h	convective heat transfer coefficient, W/m^2 K
h_e	exergy variation coefficient, W/m^2 K
h_{ex}	the local exergy variation coefficient, W/m^2 K
L	duct length, m
N_L	dimensionless duct length ($N_L = L/d_i$)
Nu	Nusselt number
N_e	dimensionless exergy variation number
p	pressure, Pa
Pr	Prandtl number
q_w	wall heat flux, W/m^2
Q	heat transfer rate, W
Re	Reynolds number
St	Stanton number
T_{fi}	inlet temperature of fluid, K
T_0	surrounding temperature, K
T_w	wall temperature, K
u_m	mean velocity of fluid, m/s
v	specific volume, m^3/kg
X	dimensionless cross section position, $X = x/d_i$

Greek symbols

ρ	density of fluid, kg/m^3
η	dynamic viscosity, kg/m s
λ	thermal conductivity of fluid, W/m K
λ'	thermal conductivity of fouling, W/m K
δ	thickness of fouling inside duct wall, m

Subscript

f	fluid
i	inlet
o	exit
w	wall

Superscripts

$'$	physical quantities related with fouling

distribution of irreversibility and entropy generation maps in the flow field and indicated that the flow geometric parameters could be selected in order to minimize the irreversibility associated with the specific problem. Nag et al. [3,4] studied second law optimization for convective heat transfer through a duct with constant wall heat flux and wall temperature. In their study, they plotted the variation of entropy generation versus the temperature difference of the bulk flow and the surface using a duty parameter. Sahin [5–9] studied the entropy generation in laminar viscous flow and turbulent flow through a duct with constant wall heat flux and wall temperature and showed that there could be an optimum size for heat exchangers and/or inlet temperature of fluid for which the total irreversibility due to heat transfer and pressure drop becomes a minimum. At the same time, the effect of temperature dependent viscosity during a heating process in laminar viscous flow and turbulent flow was investigated in his work. Sekulic and Morales [10] explored the existence of thermodynamic irreversibility extrema for laminar fluid flow with heat transfer under fully developed conditions through different cross sectional, free flow area ducts. Evaluation of the thermodynamic trade offs between simultaneous heat transfer at a finite temperature difference and flow friction was emphasized in terms of the non-dimensional entropy generation as a performance criterion. They presented the thermodynamic optimization of several ducts and showed that the minimum entropy generation design differs markedly from the design based on conventional methods. Mahmud and Fraser [11] analyzed the second law characteristics of heat transfer and fluid flow due to the forced convection of steady laminar flow of an incompressible fluid inside a channel with circular cross section and a channel made of two parallel plates. Analytical expressions for entropy generation number and Bejan number were derived in non-dimensional form using the velocity and temperature profiles. Abdul [12] presented investigations on the effect of the change of viscosity of laminar flow in an isothermal duct surface under convective heat transfer for more accurate determination of entropy generation and the required pumping power. It was found that the constant viscosity assumption might yield a significant amount of deviation in entropy generation and pumping power from that for the temperature dependent viscosity cases, especially for more viscous fluids. Hakan [13] reported an analytical study of entropy generation for semi-cylindrical ducts in laminar flow subjected to constant wall heat flux. The effects of Reynolds number, heat flux and the geometrical dimensions on entropy generation were analyzed. However, the factor of fouling, which strongly affects the performance of heat transfer and flow processes in heat transfer equipment has not always been considered in the second law analysis in the preceding literatures. Especially, the existing study on the fouling effect is only performed from the viewpoint of the first law of thermodynamics but neglects the