Computers & Fluids 107 (2015) 1–10

Contents lists available at ScienceDirect

Computers & Fluids

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

Reducing the flow mal-distribution in a heat exchanger

S.A.M. Said *, Rached Ben-Mansour, M.A. Habib, M.U. Siddiqui

Department of Mechanical Engineering, KFUPM, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form 29 June 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
Flow maldistribution
Heat exchanger
Header tube arrangement
Orifices
Nozzles

ABSTRACT

Header tube arrangements are commonly used in the heat exchangers. This arrangement is used to distribute the flow from the header into several tubes to achieve the required heat exchange. The flow mal-distribution within the tubes occurs due to the development of vena-contracta at the inlet to the tubes. In order to reduce the flow mal-distribution in the header tube arrangement, two approaches are presented in this study and solved numerically. In the first approach, the actual tube inlet is reduced by the introduction of an orifice. The results of the present study indicate that, by using orifice approach, flow mal-distribution can be reduced by approximately 12 times the original. However, the pressure drop from the heat exchanger increases by 7.8% compared to the case without orifices. In the second approach, the actual tube inlet is increased by the introduction of a nozzle. The results of the present study indicate that, by using nozzle approach, flow mal-distribution can be reduced by approximately 7.5 times the original. However, the pressure drop from the heat exchanger decreases by 9.8% compared to the case without nozzles.

1. Introduction

The heat exchangers involving header tube arrangements are mostly designed with the assumption that the flow within the tubes will be uniform after distribution from the header. However, in practice there is a flow mal-distribution within the tubes that causes variation in the performance of the heat exchanger compared to the desired design performance. This flow mal-distribution occurs due to the fact that there is a variation in the effective sizes of inlet to the tubes attached to the header of such heat exchangers. This variation in the effective sizes of tube's inlet is caused by the development of vena-contracta at the tube's inlet. The vena-contracta formed at the inlet of the tube causes the flow inlet diameter of the tube to be reduced from actual pipe diameter. Hence, the effective tube inlet diameter is always less than the actual tube diameter because of the presence of vena-contracta. This development of vena-contracta causes variation of tube inlet pressure drop along the header. Flow within a tube depends directly upon the pressure drop across that tube. Therefore, the varying tube inlet pressure drop generates flow mal-distribution within the header tube assembly.

A little research has been performed in this field. For instance, Habib et al. [1] evaluated flow mal-distribution in air-cooled heat exchangers while focusing at the inlet nozzle of the header for reducing the flow mal-distribution. They evaluated the effects of number of nozzles, nozzles location, geometry and diameter on mal-distribution inside the heat exchangers. Piątek [2] in his work concluded that the mal-distribution of the air inlet to car cooler may significantly influence the effectiveness of the heat exchanger. They mentioned that the experimental analyses considering flow mal-distribution through the heat exchangers and dealing with thermodynamic effects are rare. Mueller [3] also reported that flow mal-distribution have significant effect over the performance of heat exchangers. However Meyer and Kröger [4] concluded that the effect of flow mal-distribution is about minor i.e. up to 5%. Based on the study of gross flow mal-distribution in an experimental electrical heater, Lalot et al. [5] presented the effect of flow non-uniformity on the performance of heat exchangers. The results of their study indicates that gross flow mal-distribution leads to a loss of effectiveness of about 7% for condensers and counter flow heat exchangers, and up to 25% for cross-flow exchangers. Similar effects have been observed by Luo et al. [6]. Instead of working at the inlet nozzle, Anbumeenakshi et al. [7] performed an experimental investigation over a micro channel setup with two different type of headers namely trapezoidal and rectangular. Their results indicated that the trapezoidal header gives better performance. Tong et al. [8] numerically examined the flow distribution in multiple micro tubes for three different header geometries like linearly

* Corresponding author at: Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, P.O. Box 4, Dhahran 31261, Saudi Arabia. Tel.: +966 8601558 (O).

E-mail address: samsaid@kfupm.edu.sa (S.A.M. Said).

http://dx.doi.org/10.1016/j.compfluid.2014.09.012
0045-7930/

Nomenclature

C_μ	constant
$C_{\epsilon 1}$	constant
$C_{\epsilon 3}$	constant
D	diameter of pipes
d	diameter of orifices/nozzles
G_k	turbulent kinetic energy generation
k	turbulent kinetic energy
p	static pressure
U_j	mean velocity
x_j	coordinate
STD	standard deviation

Greek symbols

δ	Kronecker delta
ϵ	rate of dissipation of turbulent kinetic energy
μ	viscosity
ρ	density
σ	effective Prandtl number

Subscripts

t	turbulent
eff	effective

tapered distribution manifold, concave down contoured distribution manifold and concave up contoured distribution manifold assuming uniform velocity at header inlet. Header with linear taper was found to give better flow uniformity. Hassan et al. [9] performed a CFD simulation to analyze the flow mal-distribution in a modified header. Their results indicated that the header with tapered longitudinal section gives a relatively equal distribution compared to the one with uniform longitudinal section. Chen and Sparrow [10] present a method to investigate the effect of the geometric shape of the exit ports on mass flow rate uniformity effusing from a distribution manifold. The results of the per-port mass effusion normalized to the average mass-flow rate of the manifold demonstrate that the single continuous slot provides the best performance. Tuo and Hrnjak [11] investigated experimentally and numerically the flow mal-distribution caused by the pressure drop in headers and its impact on the performance of a microchannel evaporator with horizontal headers and vertically oriented tubes. Experimental results show that the flash gas bypass method almost eliminates the quality induced mal-distribution.

Kandlikar et al. [12] performed the experimental investigation of a proposed new technique to measure the flow mal-distribution in parallel channels. Another group of investigations deals with evaporators and condensers, applied in air-conditioning and refrigeration. The effects of mal-distribution in fin-tube heat exchangers, which takes place on the air-side through the fin passages as well as on the liquid side in the tube circuits, have been investigated by several researchers [13–15]. Jiao et al. [16–19] experimentally investigated the effect of distributor's inlet angle on the mass flow rate non-uniformity in plate frame heat exchangers. Jiao and Baek [20] also investigated experimentally, the effect of distributor configuration on the flow mal-distribution in plate fin heat exchanger.

It can be seen that most of the literature focused over reducing the flow mal-distribution by either working over the inlet nozzle or by working over the geometrical shape of the header. However, to the best knowledge of the authors, so far no work has been conducted over the header tube interface to reduce the flow mal-distribution. Therefore the present work is focused over reducing the flow mal-distribution by working at the header-tube interface. The mal-distribution of flow in the tubes of the heat exchanger is an important parameter to be determined for engineering design purposes. It is because of the fact that heat exchanging capability of a heat exchanger is directly dependent upon the flow rate through the heat exchanger. This mal-distribution causes an unexpected drop in the mass flow rate through the different tubes of the heat exchanger which may reduce the efficiency of the heat exchanger. An adequate analysis of flow mal-distribution in the heat exchanger can thus reduce the possibility of having an under-designed heat exchanger. Applications of such kinds of heat exchangers are in different kind of industries such as in the condensers and evaporators of the air-conditioning industry as well as the air-cooled heat exchangers in the oil industry, etc. The significance of the flow mal-distribution in a heat exchanger depends upon the operating parameters of that heat exchanger. For heat exchangers with high effectiveness or low temperature difference, even small level of flow mal-distribution becomes significant as the small non-uniformities in flow have an undesirable effect on thermal performance [21].

The present study deals with the case in which a flow enters the header in the middle and is then distributed among various tubes attached to the header of the heat exchanger. The tube mass flow non-uniformity into the tubes indirectly depends upon the velocity profile non-uniformity at the tube inlet. The velocity profile non-uniformity results in the development of vena-contracta at the inlet of the tubes. This development of vena-contracta causes varying tube inlet pressure drop along the header for different tubes. The variation in tube inlet pressure drop causes mal-distribution in the tubes. In the present study, two approaches that reduce the flow mal-distribution by balancing the tube inlet pressure drop in a header tube arrangement are presented. First approach utilizes orifices whereas the second approach utilizes nozzles to reduce the flow mal-distribution in a header tube arrangement. In the first approach, the actual tube inlet is reduced by the introduction of an orifice. The orifice diameter is maintained such that the effective tube inlet mass flow rate becomes uniform across the length of the header. In the second approach, the actual tube inlet is increased by the introduction of a nozzle. The nozzle diameter at the header is maintained such that effective tube inlet mass flow becomes uniform across the length of the header.

2. Problem description

The main objective of the study is to reduce the flow mal-distribution in the heat exchangers. Reducing the flow mal-distribution initially requires analysis of the extent of flow mal-distribution. For this purpose, a heat exchanger having a header-tube arrangement is analyzed for flow mal-distribution as shown in Fig. 1.

Fig. 1 shows the dimensions and the geometry of the problem under study. This geometry is the base case to determine the flow mal-distribution. The geometrical modifications are made on the base case geometry to achieve a more balanced flow distribution. The geometry is composed of an inlet nozzle attached to the header with nine tubes attached to the header. The length of the tubes is long enough to ensure fully developed flow at exit of tubes. The fluid enters the header through the inlet nozzle and is then distributed among the 9 tubes attached to the header. The 9 tubes are considered to have a uniform pressure outlet. It is required to analyze the flow mal-distribution among the 9 tubes by analyzing it over the half symmetry. Thus four and a half tubes are analyzed for the reduction of flow mal-distribution in the heat exchanger. The fluid