International Journal of Heat and Mass Transfer 128 (2019) 363–377

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Elliptical double corrugated tubes for enhanced heat transfer

Kristina Navickaitė [a,*], Luca Cattani [b], Christian R.H. Bahl [a], Kurt Engelbrecht [a]

[a] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] CIDEA, Interdepartmental Centre, University of Parma, Parco Area delle Scienze 181/A, I-43124 Parma, Italy

ARTICLE INFO

Article history:
Received 8 June 2018
Received in revised form 31 August 2018
Accepted 1 September 2018

Keywords:
Heat transfer enhancement
Pressure drop
Numerical simulation
Corrugated tube
Performance evaluation criteria

ABSTRACT

The thermal performance at constant pumping power conditions was numerically investigated in ellipse and super ellipse-based double corrugated tubes. A significant increase in thermal efficiency in double corrugated tubes is accompanied with a reasonable penalty in flow reduction for the cases modelled. An ellipse and a super ellipse-based double corrugated tubes were modelled at laminar fully hydraulically developed incompressible flow. Each base geometry was analysed holding either hydraulic diameter constant or the cross-sectional area constant. The pressure drop was normalized to the length of each modelled tube in order to maintain the pumping power. Thermal analysis was conducted under constant wall temperature boundary condition. The governing equations for non-isothermal flow were solved using the finite element method, and the results of the simulations were normalized to an equivalent straight tube. Numerical results predict a thermal efficiency enhanced by 400% maintaining 4.2 times lower volumetric flow rate in double corrugated tubes at the same pressure drop. The global performance evaluation criterion increases up to 14% for the double corrugated tubes with an ellipse-base and up to 11% for the tubes with super ellipse-base.

1. Introduction

Enhanced heat transfer techniques are of interest for many different industrial fields, from the food industry all the way to aerospace engineering [1–5]. These techniques are particularly interesting for industrial applications in which the thermal processing of medium and high viscosity fluids is required. Moreover, in many cases, the fluid flow is necessarily laminar and therefore the efficiency of the heat transfer apparatuses in which fluids are conveyed is inevitably penalized. Techniques producing enhanced heat transfer accompanied by reduced pumping power are in high demand in these industries. Improved heat transfer allows thermodynamic cycles to operate at conditions that are more efficient and opens new opportunities for alternative cycles and sustainable energy technologies.

Heat transfer enhancement techniques essentially reduce the thermal resistance by increasing the heat transfer coefficients with or without an increase of the heat transfer surface area. The benefits that can be derived are, for instance, the reduction of the size of the heat exchangers which can reduce cost, and the decrease of the temperature difference at which the working fluids operate which increases thermal performance or efficiency. The literature suggests to classify the techniques of enhanced heat transfer into active techniques that require a mechanical aid or electrostatic fields, passive techniques that do not require an external power and compound techniques that represent the combination of two or more different techniques [1]. Passive techniques are based on changes induced on the fluid flow through geometrical disruptions or modification of the surface, such as curvature of the walls or surfaces roughness or corrugation or through the insertion of devices in the main flow directly or by means of additives [1,6]. Since these techniques do not require any external power input, they are of great interest for industrial applications. Moreover, in the case of renovation or modification of an existing heat exchanger, the passive techniques offer much faster and easier solutions compared to active techniques. In addition, manufacturing process of realization of insertion or particular shape modifications of a tube wall is quite simple and nowadays it is a mature technology.

For all those reasons, the passive techniques became the most frequently employed for engineering applications, such as rippled and spirally corrugated tubes in systems for domestic hot water preparation using solar energy, finned tube geometries, treated surfaces, rough surfaces, displaced enhancement devices, swirl-flow devices, surface-tension devices, coiled tubes, or flow additives [1]. One of the most widely adopted passive technique is wall corrugation: the enhancement effect associated with wall corruga-

* Corresponding author.
E-mail address: knav@dtu.dk (K. Navickaitė).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.003
0017-9310/

Nomenclature

Variables

A_s	surface area, m^2
A_c	cross-section area, m^2
AR	aspect ratio
a, b	semi-major and semi-minor axes of an ellipse, m
C	heat capacity rate, W K^{-1}
c_p	specific heat, $J(kg\ K)^{-1}$
D	diameter, m
f	friction factor, –
$\bar{h}$	average local convection coefficient, $W(m^2\ K)^{-1}$
k	thermal conductivity of water, $W(m\ K)^{-1}$
$\dot{m}$	mass flow rate, kg s^{-1}
n	ellipse shape factor, –; unit normal to the surface
NTU	number of transfer units, –
Nu	Nusselt number, –
P	perimeter, m
Pr	Prandtl number, –
p	corrugation period, m
PEC	performance evaluation criteria, -
q	heat transfer, W
R	radius, m
Re	Reynolds number, –
$\bar{U}$	average overall heat transfer coefficient, $W(m^2\ K)^{-1}$
U, u	fluid velocity in x direction, m s^{-1}
x, y, z	geometric coordinates, m
$\dot{V}$	flow rate, $m^3\ s^{-1}$
ΔT	temperature difference, K
ΔT_{lm}	logarithmic mean temperature difference, K
Δp	pressure difference, Pa

Abbreviations

AEA	alternating elliptical axis
BC	boundary conditions
BL	boundary layers
CFD	computational fluid dynamics
err	error

Greek letters

ε	effectiveness, –
γ	geometric surface equation
Θ	temperature difference, K
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}

Subscripts

c	coarse
conv	convective
f	fine, fluid
h	hydraulic
i	inlet
m	mean
max	maximum
min	minimum
s	surface
o	outlet
0	straight (reference)

tion is due to the periodic interruption of the development of both the thermal and hydraulic boundary layers, an increase in heat transfer area, generation of swirling and/or secondary flows and the promotion of flow transition to an unsteady regime. They are employed in a high number of industrial applications. It has also been emphasized that corrugated tubes give an advantage for more rapid thermal food processing which is important for retaining natural and organic properties of food [7].

The main research efforts over the last five years have been focused on investigating spirally or transversally corrugated tubes and channels, fins or inserts of wavy strip tapes, and other techniques that allow disturbance of thermal boundary layers [8–16]. A concept of fluted tubes was investigated by Srinivasan et al. [12]. The definition of the shape of the cross-section of the fluted tubes was given by bore and envelope diameters, flute depth, pitch and the helix angle, which depends on the number of flute starts. Most of the investigated corrugated tubes have a non-circular cross-section, e.g. a triangle shaped cross-section or a star shaped cross-section.

Another method to increase heat transfer was presented by Guo et al. [17], who suggested that convection can be enhanced by increasing the included angle between the fluid velocity and the temperature gradient. In other words, the thermal gradient in the radial direction must be forced to be more perpendicular to the velocity profile in the flow direction. This means that the mixing of the flow should be ensured in the radial direction. This can be done by changing the boundaries of the fluid channel, and an implementation of the principles suggested by Guo et al. [17] is an alternating elliptical axis geometry (AEA) tube where the flow geometry transitions from an elliptical cross section at a specific angle to an elliptical cross section at another angle. Li et al. [18] demonstrated that AEA tubes give at least an 84% increase in heat transfer compared to a straight tube. Khaboshan and Nazif [13] performed modelling of AEA tubes for turbulent flow and showed that the tubes have an enhanced heat transfer performance at a performance evaluation criterion that is above 1 for some flow ranges. Meng et al. [19] proved experimentally that the heat transfer is 100–500% enhanced in AEA tubes for the Reynolds number (Re) region from 500 to 2300 with a 100–350% increase in flow resistance. Moreover, the Authors proposed uniform correlations for Nusselt number (Nu) and friction factor (f) in a range of Re from 500 to 50,000 for AEA tubes that have period and diameter ratio of $p/D = 2$. The uniform correlation of Nu shows that the AEA tubes exhibits early transition from laminar to turbulent flow regime.

Generally, the geometries presented in literature show an increase in Nu with increasing Re within the laminar flow regime. Research on more intensive ways to disrupt the thermal boundary layer has also been carried out. These methods include artificially increased wall roughness and different types of inserts or turbulators [20]. All the approaches discussed above increase the surface area for the heat transfer, the convection coefficient, and the pressure drop. The major attention of experimental and numerical work has been directed toward spirally corrugated tubes. Very few studies have reported results of global performance obtained using tubes, shaped in a sinusoidal manner [3,21,22]. Moreover, fewer results of experimental and modelling studies were obtained at low Re [22–28]. Generally, it was found that a significant increase in heat transfer in a corrugated tube of a given geometry is obtained in a certain range of Re number and further raising Re does not influence heat transfer as much. Hærvig et al. [3] reported that increasing the corrugation length in spirally corrugated tubes increases Nu. The same study also showed that at intense corrugations, the flow is radically different, which results in a slight increase in heat transfer, while pressure loss increases significantly.