International Journal of Heat and Mass Transfer 101 (2016) 76–90

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of wall corrugation on local convective heat transfer in coiled tubes

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 20 April 2016
Accepted 27 April 2016

Keywords:
Compound heat transfer enhancement
Helically coiled tube
Corrugated tubes
Inverse Heat Conduction Problem

ABSTRACT

The present paper presents the application of an inverse analysis approach to experimental infrared temperature data with the aim of estimating the local convective heat transfer coefficient for forced convection flow in coiled pipe having corrugated wall. The estimation procedure here adopted is based on the solution of the Inverse Heat Conduction Problem within the wall domain, by adopting the temperature distribution on the external coil wall as input data of the inverse problem: the unwanted noise is filtered out from the infrared temperature maps in order to make feasible the direct calculation of its Laplacian, embedded in the formulation of the Inverse Heat Conduction Problem, in which the convective heat transfer coefficient is regarded to be unknown. The results highlighted the local effects of both wall curvature and of wall corrugation on the convection heat transfer augmentation mechanism.

1. Introduction

Among the most common passive techniques for enhancing convective heat transfer in ducts, rough surfaces, displaced enhancement devices, swirl-flow devices, curved geometries and flow additives are found [1–3]. These techniques are usually employed alone but it is well known that, in some cases, two or more of the existing techniques can be employed simultaneously to produce an enhancement larger than that produced by using only one technique. The combination of multiple techniques acting simultaneously is known as compound enhancement [2].

Different types of compound methods have been investigated in literature in order to verify in which conditions they are able to produce an enhancement larger than that produced by only one technique.

In [4–8] the passive compound heat transfer enhancement technique achievable by combining the effect of wall curvature and of wall corrugation was proved to be an interesting solution for optimizing the performance of helical-coiled heat exchangers for medium viscosity fluids.

The enhancement effect related to the helical coiling is due to the fact that the fluid experiences the centrifugal force that causes the fluid from the core region to be pushed towards the outer wall by producing a thinning of the boundary layers. Moreover, this phenomenon causes the generation of counter-rotating vortices that produce additional transport of fluid over the cross section of the pipe, by increasing heat transfer when compared to that found in a straight tube [9]. The enhancement effect associated to the wall corrugation is instead due to the periodic interruption of the boundary layers development, to the increase in heat transfer area, to the generation of swirling and/or secondary flows and to the promotion of the transition to an unstable regime [10].

The experimental data obtained by Rainieri et al. [4–6] showed that, for low Dean number values (*De* lower than about 120 for a corrugation depth and pitch of about 1 and 16 mm respectively) the wall curvature effect prevails and the heat transfer enhancement was the same for both the corrugated and the smooth helically coiled tube. On the contrary, for higher Dean number values, the wall corrugation brought an additional heat transfer enhancement. These outcomes highlight that the wall corrugated coils are a suitable tool to increase the overall thermal performances of the apparatuses employed in industrial applications where medium viscosity fluids are encountered, like in the food, chemical and pharmaceutics industries.

This compound enhancement techniques has been mainly discussed in the available scientific literature by considering only the heat transfer performance averaged over the tube perimeter and/or over the whole heat transfer surface area. This approximated approach, which is acceptable for many applicative cases, comes from the practical difficulty of local measuring heat flux

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.106
0017-9310/

Nomenclature

Symbol	Quantity (SI unit)
a	coil diameter (m)
c_p	specific heat at constant pressure (J/kg K)
e	wall thickness (m)
De	Dean number
h	convective heat-transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m^2 K)
p	coil pitch (m)
q	convective heat flux per unit area (W/m^2)
r	radial coordinate (m)
Re	Reynolds number (–)
T	temperature (K)
u,v	frequency components (rad^{-1})
u_c	cutoff frequency (rad^{-1})
z	axial coordinate (m)
w	mean fluid axial velocity (m/s)
H	transfer function
J	influence coefficient
Q	convective heat flux (W)
Q_g	internal heat generation (W)
R_{env}	overall heat-transfer resistance between the external tube wall and the surrounding environment (m^2 K/W)
Nu	Nusselt number
Y	measured temperature (K)
α	angular coordinate (rad)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)

Subscripts, superscripts

b	bulk
env	environment
ext	external
f	fluid
int	internal

on the internal wall surface of a pipe. The size of the probes, the geometric inaccessibility of the surface, or a hostile environment prevent placing sensors on pipe internal wall. However, in some industrial applications, the knowledge of local thermal performances is of primary importance. For instance, in food pasteurisation, an excessively irregular temperature field could reduce the bacteria heat killing or locally overheat the product. Moreover, experimental data about the local convective heat transfer coefficient over the heat transfer surface could provide a deeper insight into the augmentation mechanisms for understanding the causal relationship between the heat transfer surface modification and the convection enhancement effect.

The present work aimed to start to fill this gap by presenting and testing an experimental procedure to estimate local heat-transfer coefficient in coiled tubes having corrugated wall. In order to single out the effect of wall curvature, also coiled tubes with smooth wall have been considered in the investigation.

The estimation procedure hereby presented is based on the solution of the Inverse Heat Conduction Problem (IHCP) within the wall domain by following a formulation that adopts the temperature distribution on the external coil wall as input data and in which the convective heat transfer coefficient distribution at the fluid-internal wall interface is regarded to be unknown [11]. Being the wall temperature distribution characterized by high spatial gradients, due to the complex effect of the wall corrugation on the flow pattern, the experimental methodology required a highly spatially resolved temperature measuring procedure, that was achieved by adopting a high precision cooled infrared camera. With this regard, it is worth remembering that the applications of thermographic systems to IHCPs are mainly limited to the use of focal plane array infrared cameras with cryogenic cooling, since they are characterized by a very good performance in terms of noise-equivalent temperature difference [12–14].

As it is well known, IHCPs present some problems due to the fact that they are ill-posed showing a great sensitivity to variations in the input data such as the ones deriving from the experimental noise. In order to bypass these difficulties, that are particularly critical when infrared thermography is used as temperature measuring technique, many methods, based on the processing of experimental data, have been suggested and validated in literature. Among these techniques the conjugate gradient iterative method, the Laplace transform method, the sequential function specification method, the regularization methods such as Tikhonov regularization, the mollification method, the reciprocity function approach, the truncated singular value decomposition method and the filtering technique approach method are found [15–24].

Some of these techniques have been already successfully adopted to estimate local heat transfer coefficient in different pipe geometries [19,22–24] but they have never been applied to corrugated coils. For example, Lu et al. [25] implemented an estimation approach based on the IHCP solution, using the conjugate gradient method, to estimate the unknown transient fluid temperatures near the inner wall in section of a pipe elbow with thermal stratification. Su and Hewitt [26] estimated the time-dependent heat transfer coefficient of forced convective flow boiling over the outer surface of a heater tube solving an Inverse Heat Conduction Problem based on Alifanov's iterative regularization method. Rouizi et al. [27] employed the quadrupole method to retrieve the temperature and flux distributions over the internal surface of a micro-channel using temperature profiles measured at the external surface. Local convective heat transfer coefficient in coiled tubes was experimentally evaluated by Bozzoli et al. [24] using the Tikhonov regularisation method, the quadrupole method [19] and the filtering approach [23].

From the comparison of the different estimation approaches, it comes to light that the filtering approach is particularly suitable for problems with a high number of unknown variables and for input signal that are represented by spatially highly resolved temperature maps such as the infrared maps [28]. Moreover, this approach avoids the formulation of complex algorithms because the desired information (i.e., heat transfer coefficient or heat source distribution) can be derived by directly solving the heat conduction equation which uses as input data the denoised temperature field that is obtained by filtering the raw infrared maps.

In this paper the ill-conditioned nature of the IHCP was handled by applying the filtering technique on infrared temperature maps and this enabled to obtain the distribution of convective heat transfer coefficient in corrugated coils. Furthermore, the obtained results provided an improvement of the knowledge on this interesting compound convection enhancement technique highlighting the effect of wall curvature and of wall corrugation on the heat transfer augmentation mechanism.

2. Experimental facilities and image processing procedure

In the present investigation, a corrugated wall and a smooth wall helically coiled stainless steel type “AISI 304” tubes were