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Research Paper

Geometric optimization for thermal–hydraulic performance of dimpled enhanced tubes for single phase flow

Ming Li [a], Tariq S. Khan [a,*], Ebrahim Al Hajri [a], Zahid H. Ayub [b]

[a] Department of Mechanical Engineering, The Petroleum Institute, Abu Dhabi, United Arab Emirates
[b] Isotherm Inc., Arlington, USA

HIGHLIGHTS

- Thermal–hydraulic characteristics of pipe-in-pipe heat exchanger.
- Geometric optimization of enhanced tube for optimum performance.
- Numerical simulation of enhanced tube.
- Validation of simulations with experimental data.

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ABSTRACT

Enhanced surfaces have larger heat transfer surface area and offer increased turbulence level hence allowing higher heat exchange performance. In this study, numerical simulations are conducted to simulate geometric design optimization of enhanced tubes for optimal thermal–hydraulic performance. The simulations are validated with experimental data. Two and three dimensional steady incompressible turbulent flow in dimpled enhanced tube is numerically studied using realizable k–ε method. The pressure–velocity coupling is solved by Semi-Implicit Method for Pressure Linked Equations Consistent (SIMPLEC) algorithm. Results show that dimples on tube surface present high heat transfer performance. Compared to staggered configuration, the in-line dimples arrangement provided better overall heat exchange characteristics. The geometric parameters like dimple shape, depth, pitch and starts are found to have significant effects on overall heat exchange performance while the dimple diameter has insignificant effect on thermal performance.

1. Introduction

Ever increasing energy requirements have prompted industries to adopt all measures to develop high performance thermal systems. One way of achieving high thermal performance is to use passive enhancement technologies. In order to improve thermal system efficiency, various kinds of enhancement techniques such as rough surfaces, displaced insert devices and extended surfaces have been proposed and evaluated by Bergles et al. [1]. Rough surfaces are presented in various configurations, such as discrete dimples and random sand grain roughness, Bergles and Manglik [2]. This configuration is designed to disturb and mix the boundary layer, rather to increase heat transfer area. Dimpled enhanced surfaces have been experimentally investigated by some researchers in the near past. For instance, Chen et al. and Wang et al. [3,4] studied effects of dimpled protrusions on thermal performance of tubes, effects of ribs are studied by Gee and Webb, Han and Park [5,6], while Garcia et al. [7,8] studied effects of helical wires, dimples and axial corrugations on thermal–hydraulic performance of tubes. Similarly, considerable CFD investigations on dimpled enhanced surfaces can be found in open literature. However, these simulation studies are mainly focussed on channels with cavities on the surfaces. Xie and Sundén [9] undertook numerical simulation of a rectangular channel with cavities on the bottom surface. Using realizable k–ε turbulence model, they reported that the heat transfer enhancement of dimpled channel was up to 200% with only 5% friction penalty. More recently, Xie [10] reported a similar study in square channels with different internal protruded dimple geometries. Bi et al. [11] studied a mini-channel with cavities and cylindrical grooves. They applied field synergy principle to study the heat transfer enhancement mechanism. The effects of dimple geometry, including depth, diameter and pitch, on the performance

* Corresponding author.
E-mail address: tkhan@pi.ac.ae (T.S. Khan).

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Nomenclature

A	heat transfer surface area, m^2
c_p	specific heat, J $kg^{-1}K^{-1}$
d	projected diameter of dimple, mm
D	diameter of tube, m
D_h	hydraulic diameter, mm
e	Error/deviation
f	friction factor
h_i	convective heat transfer coefficient, W m^{-2} K^{-1}
H	dimple depth, mm
k	turbulent kinetic energy, m^2 s^{-2}
L	length, m
m	exponent of Reynolds number
$\dot{m}$	mass flow rate kg s^{-1}
N	starts of dimples
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
P	dimple pitch, mm
Δp	pressure drop, Pa
q''	heat flux density, W m^{-2}
r	distance from the centreline, m
Re	Reynolds number
T	temperature, K
ΔT_m	logarithmic mean temperature, K
u	velocity, m s^{-1}
u^*	friction velocity
V_c	centreline velocity, m s^{-1}
y	distance from the wall, m
y^+	mesh resolution indicator

Greek symbols

υ	kinematic viscosity, m^2 s^{-1}
ε	rate of energy dissipation
μ	dynamic viscosity, Pa S
ρ	density, kg m^{-3}
Γ	production rate of κ, m^2 s^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}

Subscripts

c	centre
eff	effective
exp	experimental
i	horizontal direction
j	vertical direction
max	maximum
num	numerical
s	smooth tube
ref	reference

of a heat transfer unit were investigated. Fan and Yin [12] investigated the effects of geometrical parameters of protrusions on the heat transfer and pressure drop of dimpled jacket of an evaporator. They used standard k–ε model to predict turbulent flow. The distance between protrusions was reported to have considerable effect on heat transfer. Similarly, the in-line configuration has been shown to have better thermal–hydraulic performance compared to staggered arrangement. All these reported studies revealed that surfaces with dimples/cavities can provide a realizable heat transfer enhancement with relatively low pressure drop penalty. Though, considerable studies have been conducted on enhanced surfaces with respect to thermal performance evaluation, however, most of the previous studies are restricted to specific geometries and flow conditions. It is known that enhanced tubes can involve several geometric parameters and their configurations so lack of thermal–hydraulic data is still a barrier in the use of these surfaces in heat exchanger industry.

In addition to providing area enhancement effect, the dimpled surfaces disturb viscous sublayer allowing early transition to flow turbulence. Simulations to carry out parametric studies including various geometric variations of dimpled enhanced tubes can help manufacturers do pre-assessment studies to figure out most efficient dimple configurations for actual testing. Current study aims to provide such an assessment tool by carrying out CFD simulations to estimate heat transfer and pressure drop for dimpled enhanced tubes. This investigation focuses on parametric study of the design factors affecting thermal–hydraulic performance of dimpled tubes. Further work may be needed to optimize the design. Several enhanced tube geometries and their configurations have been simulated to optimize thermal–hydraulic performance.

2. Physical model

A simplified drawing of the enhanced tube used in current simulations is shown in Fig. 1(a) while definitions of geometrical parameters are presented in Fig. 1(b).

Table 1 lists geometrical dimensions of the simulated enhanced tubes. As could be seen, fifteen different combinations of enhanced tube configurations have been tested in the current study. The simulation efforts focus on optimizing the heat transfer and pressure drop by changing key geometrical parameters such as shape, dimple depth, dimple diameter, pitch, start and configuration. Starts is a standard term used to describe the number of dimples at a circumferential location.

It should be noted that only tube 15 was previously tested experimentally by Li et al. [13]. They carried out their experiments on an enhanced tube in a pipe-in-pipe heat exchanger to study single phase (liquid to liquid) heat transfer and pressure drop. The heat exchanger was configured in a counter flow arrangement to achieve high temperature difference. They varied the Reynolds number from 500 to 8000 with water and 150 to 2000 for 20% water–glycol solution as working fluid.

3. Computational details

3.1. Overview

The commercial CFD software Fluent version 14.0 was used to solve 2D and 3D steady incompressible turbulent flow and heat transfer in smooth and enhanced tubes. For smooth tube, 2D model was applied due to its axisymmetric characteristics. A 3D model was generated for enhanced tube because the dimples were distributed on tube surface in staggered and in-line arrangement. The realizable k–ε model was employed to investigate influence of dimples on turbulent flow and temperature field for enhanced tubes. The pressure–velocity coupling in steady state is solved by Semi-Implicit Method for Pressure Linked Equations Consistent (SIMPLEC). Commercial software Gambit was used to generate grid system for 2D and 3D geometries.

Water was used as the working fluid and properties of water were assumed to be constant. This assumption is valid for water within the operating temperature range. Furthermore, the proper-