Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Mass Transfer 51 (2008) 2950–2966

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Investigation of dimpled fins for heat transfer enhancement in compact heat exchangers

Mohammad A. Elyyan, Ali Rozati, Danesh K. Tafti *

High Performance Computational Fluids-Thermal Sciences and Engineering Laboratory, Mechanical Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Received 23 March 2007; received in revised form 10 September 2007
Available online 5 November 2007

Abstract

Direct and Large-Eddy simulations are conducted in a fin bank with dimples and protrusions over a Reynolds number range of $Re_H = 200$ to 15,000, encompassing laminar, transitional and fully turbulent regimes. Two dimple-protrusion geometries are studied in which the same imprint pattern is investigated for two different channel heights or fin pitches, Case 1 with twice the fin pitch of Case 2. The smaller fin pitch configuration (Case 2) develops flow instabilities at $Re_H = 450$, whereas Case 1 undergoes transition at $Re_H = 900$. Case 2, exhibits higher Nusselt numbers and friction coefficients in the low Reynolds number regime before Case 1 transitions to turbulence, after which, the differences between the two decreases considerably in the fully turbulent regime. Vorticity generated within the dimple cavity and at the dimple rim contribute substantially to heat transfer augmentation on the dimple side, whereas flow impingement and acceleration between protrusions contribute substantially on the protrusion side. While friction drag dominates losses in Case 1 at low Reynolds numbers, both form and friction drag contributed equally in Case 2. As the Reynolds number increases to fully turbulent flow, form drag dominates in both cases, contributing about 80% to the total losses. While both geometries are viable and competitive with other augmentation surfaces in the turbulent regime, Case 2 with larger feature sizes with respect to the fin pitch is more appropriate in the low Reynolds number regime $Re_H < 2000$, which makes up most of the operating range of typical compact heat exchangers.

Keywords: Dimples; Compact heat exchangers; LES

1. Introduction

The science and engineering of air-side heat transfer enhancement plays a critical role in the design of compact heat exchangers. Typically, air-side resistance to heat transfer contributes between 80 and 90 percent of the total resistance to heat flow. Commonly, densely packed fins are used to increase the air-side surface area and also play the dual role of increasing the heat transfer coefficient. This is accomplished by using various topologies such that the thermal boundary layer is constantly regenerated either by interrupted surfaces and/or inducing self sustained flow oscillations. Wavy fins, offset strip fins, and louvered fins are common examples. An additional aspect which any design has to be sensitive to is the friction penalty of achieving enhanced heat transfer. Hence, surface topologies which maximize heat transfer augmentation with minimal friction penalty are sought.

Recently surfaces imprinted with dimples or concave indentations have been researched extensively. One of the early investigations was conducted by Afansayev et al. [1], who investigated the effect of applying shallow dimples ($\delta/D = 0.067$) on flat plates on the overall heat transfer and pressure drop for turbulent flow. Significant heat transfer augmentation (30–40%) at negligible pressure drop augmentation was reported. Since then a number of experimental investigations have been conducted for different dimple geometries yielding heat transfer augmentation

* Corresponding author.
E-mail address: dtafti@vt.edu (D.K. Tafti).
URL: http:www.hpcfd.me.vt.edu (D.K. Tafti).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.09.013

Nomenclature

D	dimple imprint diameter
C_f	fanning friction coefficient
f	non-dimensional frequency based on mean velocity and fin pitch
g^{ij}	contravariant metric tensor
k	thermal conductivity
S	stream-wise pitch
P	span-wise pitch
H	channel height or fin pitch (characteristic length scale)
L_x	periodic length
$\vec{n}$	surface normal vector
Nu	Nusselt number
p	fluctuating, modified or homogenized pressure
Pr	Prandtl number
q''	constant heat flux on channel walls
Re_τ	Reynolds number based on friction velocity (u_τ)
Re_H	Reynolds number based on mean flow velocity
Q_x	flow rate in the streamwise direction
t	non-dimensional time based on u_τ and H
Time	Non-dimensional time based on u_b and H
$\vec{u}$	cartesian velocity vector
u_τ	friction velocity (characteristic velocity)
u_b	mean flow velocity
$\vec{x}$	physical coordinates
β	mean pressure gradient
δ	dimple depth
γ	mean temperature gradient
θ	fluctuating, modified or homogenized temperature
Ω	heat transfer surface area
$\vec{\xi}$	computational coordinates

Subscripts

b	bulk
D_h	based on the hydraulic diameter of the channel
H	based on channel height
o	smooth channel
t	turbulent parameters
τ	values based on friction velocity

Superscripts

+	wall coordinates
*	dimensional quantities

factors of about 2–2.5 with low frictional losses compared to other surfaces with flow turbulators [2].

Most experimental studies were conducted in the fully turbulent flow regime; the few low Reynolds number studies conducted were mainly concerned with flow visualization, which showed periodic and continuous shedding of a primary vortex pair from the central portion of the dimple, in addition to a secondary vortex pair shed from the span-wise edges of the dimple (Mahmood et al. [3], Ligrani et al. [4,5]). Heat transfer distribution and local Nusselt number variation on the dimpled surface showed the existence of a low heat transfer region in the upstream half of the dimple cavity followed by a high heat transfer region in the downstream half. Additional regions of high heat transfer were identified at the downstream rim of the dimple. A number of studies have reported significant heat transfer augmentation at low pressure drop penalty (Mahmood et al. [3], Ligrani et al. [5], Chyu et al. [6], Moon et al. [7], Burgess and Ligrani [8] and Ekkad and Nasir [9]).

Study of the different geometrical factors resulted in the conclusion that the channel height to dimple imprint diameter ratio (H/D) and the dimple depth to dimple imprint diameter ratio (δ/D) play a significant role in the heat transfer and flow structure inside the domain. Ligrani et al. [4] reported that as H/D decreased the secondary flow structures and flow mixing intensified. Nevertheless, Moon et al. [7] obtained almost a constant heat augmentation ratio of 2.1 for a dimpled passage with $H/D = 0.37$, 0.74, 1.11 and 1.49, but their experiments were conducted in the fully turbulent flow regime ($Re \sim 12{,}000$–$60{,}000$). Burgess and Ligrani [8] reported that both Nusselt number and friction augmentation increased as (δ/D) increased.

The use of two dimpled surfaces on opposite walls was studied by Borisov et al. [10], where highest heat transfer enhancement was reported at $Re \approx 2500$. The use of dimples on rotating channel surfaces has been studied by Griffith et al. [11] who reported a heat transfer augmentation of 2.0. The effect of using spherical dimples and protrusions on opposite walls of the channel was studied by Ligrani et al. [12] and Mahmood et al. [13], where only the dimpled side of the channel was heated. Intensified secondary flow structures, flow unsteadiness and heat transfer augmentation were reported. Moon et al. [14] studied the effect of gap clearance in a channel with protrusions only on one side of the channel, where heat distribution showed high heat transfer augmentation at the front of the protrusion and in the passage between protrusions.

Numerical study of the problem of dimpled channel flow was conducted by a number of researchers. Wang et al. [15], using laminar flow simulation, identified a symmetric 3D horseshoe vortex inside a single dimple. Lin et al. [16], Isaev and Leont'ev [17], Park et al. [18], Won and Ligrani [19] and Park and Ligrani [20] used steady state Reynolds Averaged Navier Stokes (RANS) modeling to study flow and heat transfer in dimpled channel in the turbulent regime. All of the RANS calculations were done in the fully turbulent flow regime. Patrick and Tafti [21] used Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) to predict the heat transfer and friction coefficient augmentation in a channel with one dimpled