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Laminar heat transfer enhancement downstream of a backward facing step by using a pulsating flow

A. Velazquez [a,*], J.R. Arias [a], B. Mendez [b]

[a] *Propulsion and Fluid Mechanics Department, School of Aeronautics, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain*
[b] *Fluid Mechanics Area, Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911 Leganés, Madrid, Spain*

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Abstract

This study is motivated by the need to devise means to enhance heat transfer in configurations, like the back step, that appear in certain types of MEMS that involve fluid flow and that are not very efficient from the thermal transfer point of view. In particular, the work described in this paper studies the effect that a prescribed flow pulsation (defined by two control parameters: velocity pulsation frequency and pressure gradient amplitude at the inlet section) has on the heat transfer rate behind a backward facing step in the unsteady laminar 2-D regime. The working fluid that we have considered is water with temperature dependent viscosity and thermal conductivity. We have found that, for inlet pressure gradients that avoid flow reversal at both the upstream and downstream boundary conditions, the time-averaged Nusselt number behind the step depends on the two above mentioned control parameters and is always larger than in the steady-state case. At Reynolds 100 and pulsating at the resonance frequency, the maximum time-averaged Nusselt number in the horizontal wall region located behind the step whose length is four times the step height is 55% larger than in the steady-case. Away from the resonant pulsation frequency, the time-averaged Nusselt number smoothly decreases and approaches its steady-state value.

Keywords: Back; Step; Unsteady; Laminar; Pulsating

1. Introduction

Nowadays, there is a large variety of Micro-Electro-Mechanical systems (MEMS) that, in one way or another, involve fluid flow and heat transfer effects. Practical applications of these systems include, for instance, micro-motors, micro-cooling devices and power-MEMS. When dealing with specific engineering design aspects, it often happens that because of manufacturing restrictions, or the need to keep a low product cost, channel configurations inside this type of MEMS are far from being fully optimised. For example, it is not unusual to find deep recess, sharp bends, grooves, and both forward and backward facing step like structures inside some designs. Since the surface to volume ratio grows when the typical characteristic length of the system diminishes, associated heat losses could become important and corrective actions might be implemented. In some specific cases, heat losses are so critical that new configurations need to be devised to fulfil certain objectives. For instance, micro-combustion based on arrays of catalytic wires is being pursued actively because thermal losses in the micro-scale may prevent combustion to occur in the shape of a conventional stabilised flame.

The objective of this paper is to study the effect that forced flow pulsation may have on laminar heat transfer enhancement behind a 2-D backwards facing step. We have chosen this configuration because it represents a broad class of geometries to be found inside fluid-thermal MEMS. Since we foresee liquid cooling applications, the focus of our study is on the laminar, unsteady, incompressible flow regime. For instance, if we consider a backwards facing step whose inlet channel has an height of 225 μm

* Corresponding author. Tel.: +34 91 336 6351.
E-mail address: avelazquez@aero.upm.es (A. Velazquez).

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Nomenclature

Latin symbols

a_2	control parameter for pressure gradient at inlet section
$c_{p\infty}$	specific heat at inlet section
D_h	hydraulic diameter of the inlet channel
eq_27	acronym for Eq. (27)
Gr	Grashof number
g	gravity constant
h_x	local convection coefficient behind the step
k	dimensionless thermal conductivity
k'	thermal conductivity
k_∞	thermal conductivity at inlet section
Nu_x	local Nusselt number behind the step
n	direction normal to a surface
P	dimensionless pressure
P'	pressure
Pr	Prandtl number
Re	Reynolds number based on D_h and u_∞
$Re_{\delta'}$	Reynolds number based on the Stokes thickness
RHS	acronym for right hand side
t	dimensionless time
t'	time
t^*	dimensionless pseudo-time
T	dimensionless fluid temperature
T'	temperature
T_∞	fluid temperature at inlet section
u	dimensionless horizontal velocity component
u_{max}	maximum centreline velocity in a Poiseuille type solution
u'	horizontal velocity component
u_∞	mean horizontal velocity component at inlet section
v	dimensionless vertical velocity component
v'	vertical velocity component
x	dimensionless horizontal co-ordinate
x'	horizontal co-ordinate
y	dimensionless vertical co-ordinate
y'	vertical co-ordinate

Greek symbols

β	pseudo-compressibility parameter
β_{exp}	thermal expansion coefficient
δ'	stokes layer thickness
Δ	increment
Φ	functional approximation for the Finite Point algorithm
λ_0 to λ_5	parameters that define the functional approximation Φ
μ	dimensionless dynamics viscosity
μ'	dynamic viscosity
μ_∞	dynamic viscosity at inlet section
ν'	kinematic viscosity
ρ_∞	density at inlet section
ω	dimensionless pulsation frequency
ω'	dimensional pulsation frequency

Superscripts

k	time instant
o	initial time in the integration loop

(hydraulic diameter D_h equal to 450 μm), an step height of 225 μm, and water flows in at 293 K and 0.22 m/s, the Reynolds number based on the mean inlet velocity and hydraulic diameter is 100.

Also, we will concentrate on the 2-D regime because the onset of 3-D effects is expected to occur at higher Reynolds numbers. Armaly et al. [1] reported, based on their own experimental data, a critical Reynolds number of 400 for this onset. Durst and Pereira [2] found good agreement between experimental and numerical 2-D results for Reynolds numbers below 648. Kaiktsis et al. [3], by using direct numerical simulation, suggested that the critical Reynolds number is 700. More recently, Barkley et al. [4] have shown, by performing a stability analysis, that the onset of 3-D effects starts a Reynolds 997 (this figure has been corrected to be consistent with the Reynolds number definition used in Refs. [1–3] and in the present study). Barkley et al. [4] have also discussed in detail these discrepancies and concluded that the reason for the rather low critical Reynolds number (400) found by Armaly et al. [1] is the presence of end wall effects. In particular, the span-wise aspect ratio of their experimental set up was 36:1, while Barkley et al. [4] considered an ideal 2-D geometry in their computations. Summarizing, since we will consider Reynolds numbers of the other of 100, we can assume that the hypothesis of two-dimensionality is well satisfied. We also include in our analysis the temperature dependence of both viscosity and thermal conductivity. Water viscosity changes by a factor of three in the temperature span ranging from 293 K to 353 K that we have considered, see Incropera and DeWitt [5], and that is typical of some electronics systems cooling applications. Since flow topology is very sensitive to the Reynolds number in the regime that we consider, see [1,2], we decided to account for real fluid effects from the outset.

The idea of using pulsating flows to enhance laminar heat convection is not new although the outcome of the many studies that have been performed up to now still remains controversial. The situation is best summarised in the introduction of the paper published by Yu et al. [6] where they classify previous work into four categories according to the conclusion being reached: