istegim2019:283999

EFFECTS OF INLET MANIFOLD GEOMETRY ON THE LAMINAR TO TURBULENT TRANSITION OF GAS MICROFLOWS IN ADIABATIC RECTANGULAR MICROCHANNELS

Danish Rehman*[1], Davide Barattini[1], and GianLuca Morini[1]

[1]**Microfluidics Lab., University of Bologna, Via del Lazzaretto 15/5, 40131 Bologna, Italy**

Abstract

In this work, a combined experimental and numerical campaign to investigate the effects of inlet manifold shape on the laminar to turbulent transition of gas microflows is carried out. Four rectangular microchannels are micromilled in PMMA plastic with D_h ranging from 250-330 μm and constant length of 54 mm. An attempt has been made to keep the aspect ratio ($\alpha = \frac{h}{w}$) constant, however in manufactured microchannels it varies between 0.4-0.48. Four different inlet shapes namely sudden contraction (SC), rounded entrance (RE), V shape (VS) and bellmouth (BM) are investigated in current work. In parallel, validation of an intermittency based transitional turbulence model is also performed using experimental results. Experimental results show that laminar to turbulent transition is delayed the most for BM inlet manifold shape with critical Reynolds number (Re_c) of ∼3470. It was followed by SC and VS. The smallest Re_c resulted in case of RE where laminar to turbulent transition initiated around $Re \sim 2090$. Numerical results also showed the same pattern with BM having the highest Re_c followed by SC, whereas no appreciable difference is observed between VS and SC. Experimental results have also demonstrated that gas flow with BM entrance shape microchannel undergoes the longest transitional regime with $\Delta Re_{LT} \sim 5687$ between onset of transition to fully turbulent flow, followed by RE where $\Delta Re_{LT} \sim 4554$. SC and VS entrances show relatively abrupt transition with ΔRe_{LT} of ∼3200 and ∼1680 respectively. Both experimental and numerical results have demonstrated that inlet manifold shape plays a determining role on the onset as well as length of transitional regime for gas microflows. A good agreement between experimental and numerical Re_c enables the use of intermittency based transitional turbulence model for hydraulic and thermal design of micro heat exchanging systems in product development stages.

KEYWORDS: pressure drop, friction factor, RANS transitional modeling, internal flow

1. INTRODUCTION

Knowledge of turbulent transition in rectangular microchannels (MCs) is of prime importance as such geometries are being extensively employed in MC heat sinks and MC heat exchangers. Flow transition and consequent turbulent flow is of benefit for increased mixing and heat transfer in microsystems. After the pioneering work of Tuckerman and Pease [1], most of earlier experimental groups have reported an anticipated flow transition in MCs [2] while a few groups [3] confirmed the agreement with the macro scale theory. Starting with Osborne Reynolds [4] more than a century ago, turbulent transition within wall bounded flows has been investigated mainly through experimental observations. Similarly, flow visualization as well as pressure drop studies have been utilized to observe Re_c of microflows. For liquid flows, μPIV studies were conducted by Li and Olsen [5]. They experimented four MCs with almost same hydraulic diameter (D_h) with aspect ratios (α) between $0.2-1$. They found that Re_c increased from 1715 to 2315 by decreasing α from 1 to 0.2. Similar experimentation was also performed by Wibel and Ehrhard [6] where they reported that an increase in Re_c from 1600 to

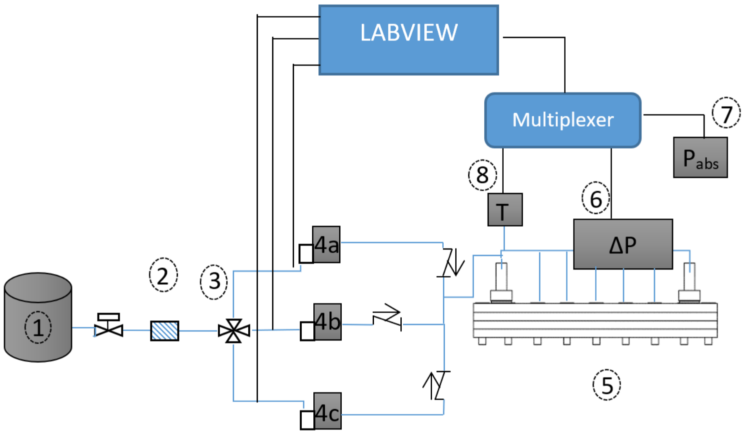
*corresponding author: danish.rehman2@unibo.it

2200 is observed for a decrease in α from 1 to 0.2. Both studies showed conformance with macro scale results. More recently Kim [7] presented experimental results of fluid flow and heat transfer for 10 chips containing 10 parallel MCs each. The critical Reynolds number increased from 1700 to 2400 with a decrease in the aspect ratio from 1.0 to 0.25. Unlike the previous μPIV studies MC dimensions are changed such that α and D_h varied simultaneously. Due to relatively higher density of seeding particles, μPIV cannot be applied to gas flows in MCs and therefore a pressure drop study (Moody chart) remains the only dispensable tool to observe turbulent transition. Such analysis for gas flows in 11 different microtubes with $D_h = 125 - 180\ \mu m$ has been presented by Morini et al. [8]. By comparing their results with previously published gas flow pressure drop studies, it was shown that if friction factor is calculated by taking into account compressibility effects and minor losses, Re_c was in between $1800 - 2000$, contrary to anticipated transitions reported by other groups [2, 9]. Aside from experimental and analytical observations, DNS has been applied to understand the physics of flow transition [10, 11, 12]. However due to the lower computational cost, RANS based turbulence modeling is preferred in industrial environments for engineering approximations. A major breakthrough in modeling transitional flow using two equations turbulence models is due to Menter et al. [13]. They augmented original SST $k - \omega$ model [14] to incorporate flow transition based upon two additional intermittency transport equations. This model was later modified to be implemented into commercial CFD codes [15]. Although originally developed for external flows, model constants were modified by Abraham et al. [16] to predict transition in internal flows. It was shown for pipe flow that fine tuned model predicted laminar and fully turbulent friction factors similar to that of Poiseuille's law and Blasius law respectively. Therefore transitional behaviour was deemed to be representative of the reality. The same transitional turbulence model was later used by Minkowycz et al. [17] to investigate the effect of turbulence intensity (TI) on laminar to turbulent transition for straing pipe flow. For TI=10%, transition was delayed and abruptly reached fully turbulent state whereas for TI=5% transition initiated around 3000 and gradually developed to fully turbulent.

While reporting the transitional characteristics of microflows much less attention has been paid to the inlet characteristics of the MCs. It has been shown by Ghajar et al. [18] and Tam et al. [19] that for conventional sized pipes, inlet shape has a significant effect on the transition and hence heat transfer. Similar study was repeated more than 20 years later for rectangular MCs by Dirker et al. [20] where they employed three different inlet manifold shapes namely sudden contraction, bellmouth, and swirl inlet. Results showed that sudden contraction shows the most delayed transition at around Re of 2000 whereas swirl inlet type showed the transition as early as Re of 1500. Studies by both of above mentioned groups employed liquid flows as working fluid. Although effects of different inlet shapes using air in a conventional sized duct have recently been reported by Moruz et al. [21] but no such study, experimental or numerical, up to this point has been reported with gas flows inside MCs. This serves as the main motivation to carry out the current investigations. Secondly, Re_c from a RANS based transitional turbulence model for the experimental configurations studied is also compared with experimental results to assess the applicability of such model for the prediction of flow behavior in transitional regime.

2. EXPERIMENTAL SETUP

A schematic of experimental test bench used in this work is shown in Fig. 1a. Pressurized Nitrogen gas is allowed to enter the MC assembly perpendicular to the axial direction of MC and leaves perpendicularly as well through outlet manifold. A detailed description of sensors used and associated uncertainties is documented in [22] and therefore is not repeated here. Four rectangular MCs are micromilled with different inlet manifold shapes namely bellmouth (BM), sudden contraction (SC), rounded entrance (RE) and V shape (VS), by following a similar methodology as reported in [22]. Resulting MCs are shown in Fig. 1b and associated dimensions that is width (w), height (h) and aspect ratio ($\alpha = \frac{h}{w}$) are reported in Table 1. Considering one dimensional flow of ideal gas, average Fanning friction factor between inlet '*in*' and outlet '*out*' of a MC with hydraulic



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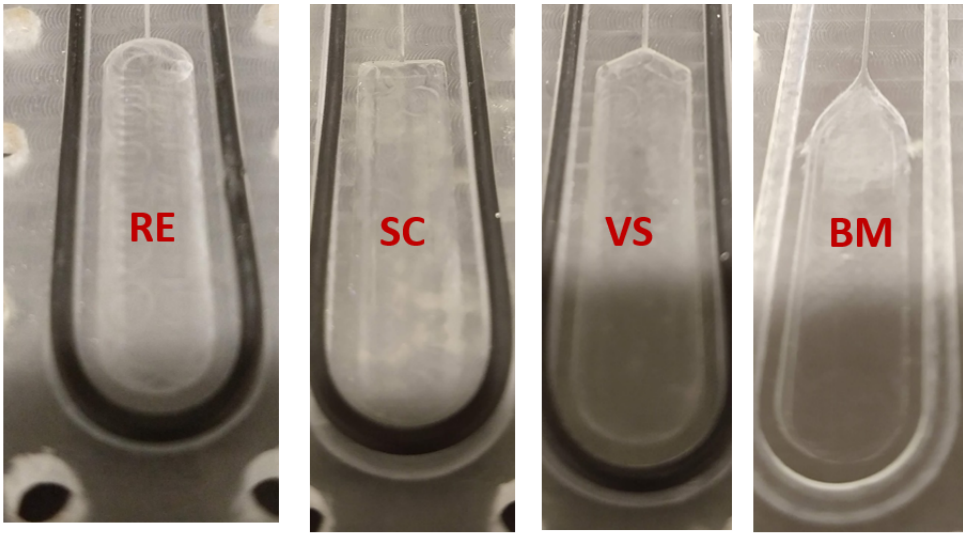

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Figure 1: Experimental setup (**a**), and fabricated manifold shapes (**b**).

Table 1: Channels geometry used for experiments.

Channel	h (μm)	w (μm)	L (mm)	α	D_h (μm)
SC	235	490	54	0.48	317
VS	245	505	54	0.485	330
RE	235	495	54	0.475	318.5
BM	180	452.5	54	0.398	2567

diameter D_h and length L can be defined by the following expression for a compressible flow [22]:

$$f_f = \frac{D_h}{L}\left[\frac{p_{in}^2 - p_{out}^2}{RT_{av}\dot{G}^2} - 2\ln\left(\frac{p_{in}}{p_{out}}\right) + 2\ln\left(\frac{T_{in}}{T_{out}}\right)\right] \tag{1}$$

where p and T denote cross sectional average pressure and temperature of gas, T_{av} is the average temperature of the gas between inlet and outlet of MC, and $\dot{G}$ is mass flow per unit area ($\dot{G} = \frac{\dot{m}}{A}$). Reynolds number at the inlet of MC is calculated using measured mass flow rate and calculated viscosity (μ) at inlet temperature with the following equation:

$$Re = \frac{\dot{m}D_h}{\mu A} \tag{2}$$

3. NUMERICAL SETUP

While conducting numerical simulations, care has been taken to account for all the geometrical features of the experimental set-up as shown in Fig. 2 which depicts MC with BM inlet shape as a representative case. The computational domain for all the cases comprised of the micro channel, inlet manifold (of respective shape), an outlet manifold and two inlet/outlet reducers. Inlet reducer connects the test section assembly to the piping from the volume flow meter whereas outlet reducer vents the gas exiting from MC to the atmosphere.

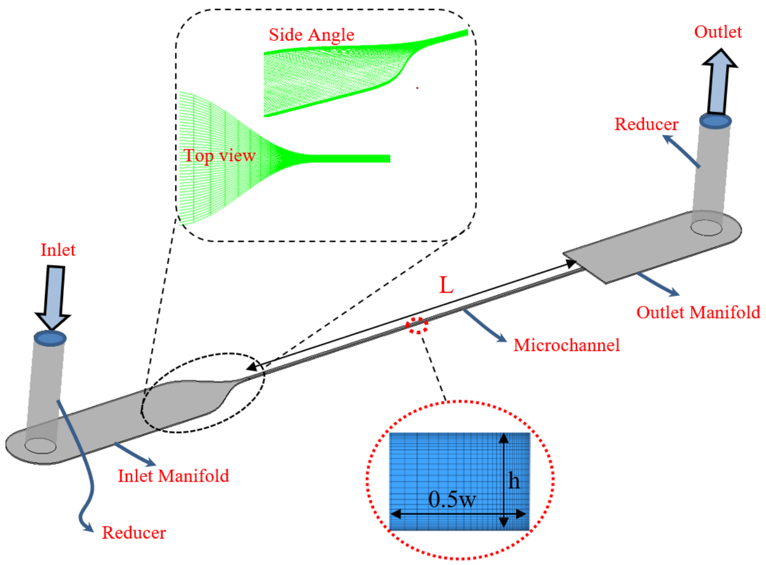


Figure 2: Geometric model used for numerical analysis of MC with bellmouth (BM) inlet.

In current set of simulations, importance has been given to the joining part of the manifold and MC and mesh is significantly refined in this zone. A structured mesh of 45×35 is used for cross section of MC and manifolds whereas number of divisions along the lengths of MC and manifolds are given to be 100 and 40 each (both inlet and outlet), respectively. A dense mesh in the cross section ensured that non dimensional geometric distance of the fist node element from the MC wall (y^+) stayed lower than 1.1 for all the simulated cases.

Steady state RANS simulations are performed for all turbulent cases. Laminar flow solver is used for the cases where $Re \leq 1000$ and for $Re > 1000$, SST k-ω transitional turbulence model is used. A modified formulation of γ-Re_θ transition turbulence model for internal flows is applied as presented by Abraham et al. [16]. High-resolution turbulence numerics are employed with a higher order advection scheme available in CFX. Pseudo time marching is done using a physical timestep of 0.001s. A convergence criteria of 10^{-6} for RMS residuals of governing equations is chosen while monitor points for pressure and velocity at the MC inlet and outlet are also observed during successive iterations. In case where residuals stayed higher than supplied criteria, the solution is deemed converged if monitor points did not show any variation for 200 consecutive iterations. Reference pressure of 101 kPa was used for the simulation and all the other pressures are defined with respect to this reference pressure. Due to small measured surface roughness for the MCs fabricated previously with similar strategy [22], walls of the MC are treated as smooth in numerical model. A no slip boundary condition is applied at the walls which essentially means that fluid particles move with the velocity of the wall which in current case is zero. Energy equation was activated using total energy option available in CFX which adopts energy equation without any simplifications in governing equations solution. Kinematic viscosity dependence on gas temperature is defined using Sutherland's law.

$$\mu = \mu_{ref} \left(\frac{T}{T_{ref}}\right)^{\frac{3}{2}} \left(\frac{T_{ref}+S}{T+S}\right), \tag{3}$$

where constants for Nitrogen gas are:

$$\mu_{ref} = 1.7812 \times 10^{-5}\,\mathrm{Pa\,s}$$
$$T_{ref} = 298.15\,\mathrm{K}$$
$$S = 111\,\mathrm{K}$$

To simulate the desired Re at the inlet boundary condition of the MC, $\dot{m}$ is varied using Eq. 2. Two planes at x/L of 0.001 and 0.9995 are treated as inlet and outlet of MC respectively, where fluid properties are extracted and further postprocessed to calculated the average f_f utilizing Eq. 1.

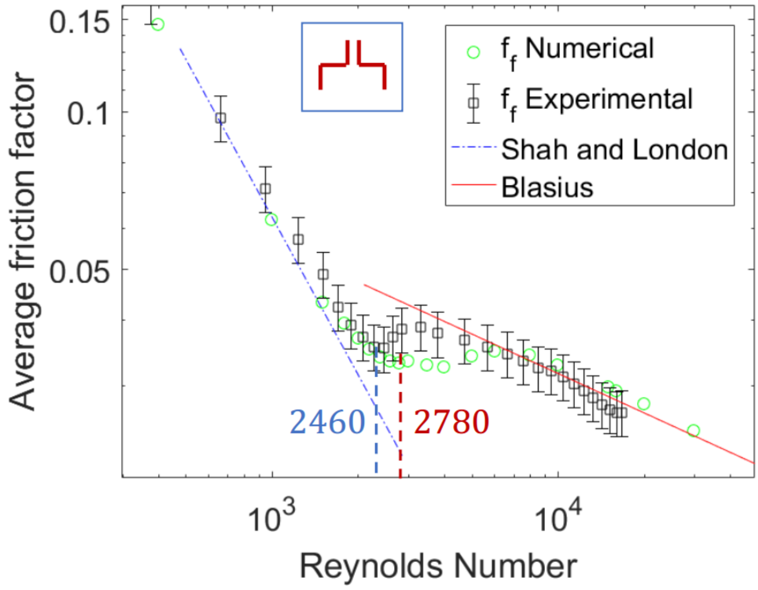
4. RESULTS

Laminar to turbulent flow transition is established using the average friction factor curve. Re_{cr} is defined as the Reynolds number in correspondence of which the friction factor attains its first minimum and then starts to increase. This point is individuated during MATLAB post processing of experimental and numerical results. A comparison between numerical and experimental friction factor is made in Fig. 3 for SC and VS MCs. There exists an excellent agreement between the current numerical results and experimental results in the laminar flow regime where f_f follows the Shah & London correlation (S&L):

$$f_{f_{SL}} = \frac{96}{Re}\left(1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5\right) \tag{4}$$

In the turbulent flow regime, both experimental and numerical results are slightly above or below the Blasius law. However even in the turbulent regime numerical f_f is within uncertainty of experimental results. Similar observations can be made for the other two MCs tested as shown in Fig. 4.The agreement between experimental and numerical results worsens in the transient regime where difference between them is almost 30% in the case of BM entrance.

Experimental results show that out of all the four inlet shapes employed in current study, BM shows the most delayed flow transition with $Re_c \sim 3470$. This is due to gradual change of flow area from manifold to microchannel inlet that helps maintaining the developed parabolic profile at the inlet of microchannel. Current findings on the delayed transition in case of BM are consistent with earlier experimental studies of Ghajar et al. [18] and Tam et al. [19] on the circular tubes of 15.8 mm and 19.1 mm. However this is in contradiction to the results presented by Dirker et al. [20] where Re_c exhibiting major transition with BM inlet shape was reported to be 1800 for a microchannel with D_h =1.05 mm and SC inlet instead showed the delayed transition at Re_c of 2000. It is to be noted that all these studies dealth with liquid flows whereas more recently Moruz et al. [21] used air to analyze the effects of inlet shapes on flow transition in a rectangular channel with α of 0.05. Similar to current results, they also observed that BM inlet shape causes the laminar flow to persist for longer range of Re ($Re_c = 3800$) compared to other inlet shapes that were experimented. Delayed transition for BM in current study is followed by SC, VS and RE inelt shapes where experimental results indicate a Re_c of ∼2460, ∼2290



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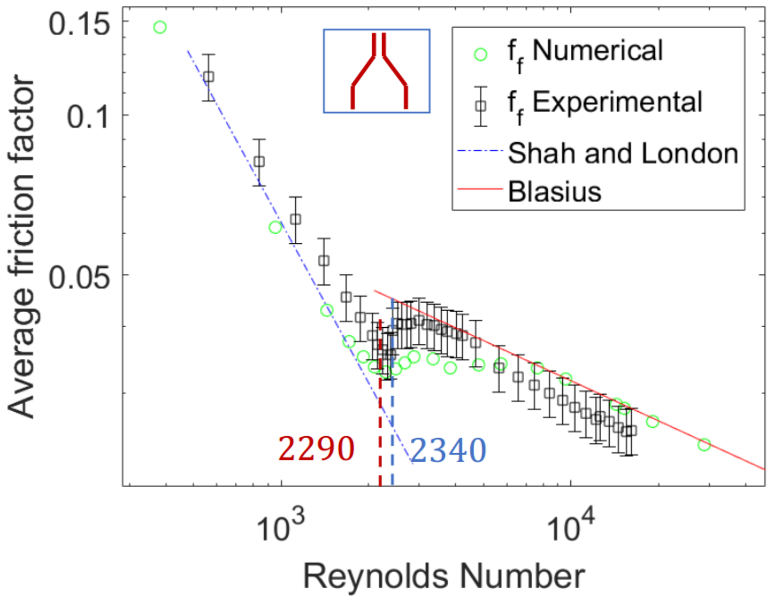

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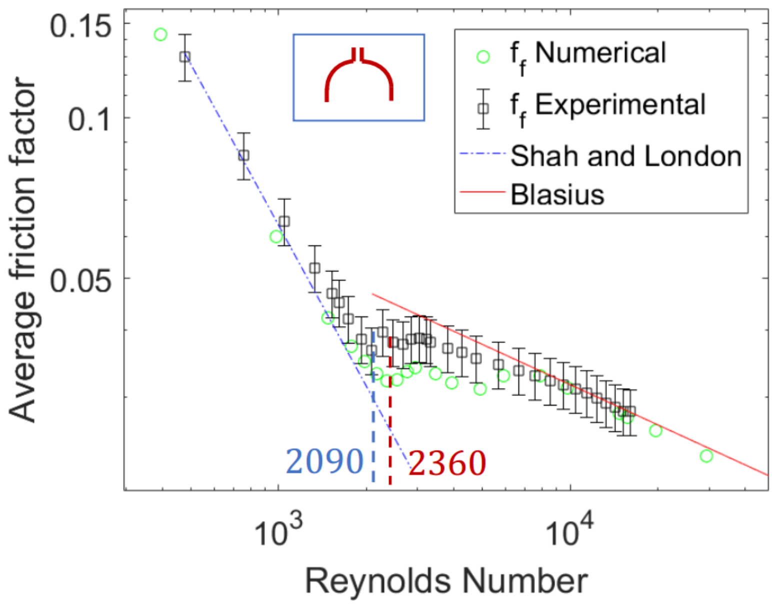
Figure 3: Friction factor for SC (**a**), and VS (**b**): blue and red vertical lines denote experimental and numerical Re_c respectively.

and ∼2090 respectively. Current numerical results of BM shape are in accordance with experimental results and show the delayed transition with numerical Re_c 13% lower than experimentally observed value. In case of SC, numerical results indicate the Re_c of ∼2780 which is again 13% higher than experimental values but nonetheless follow the trend of experimental friction factor in transitional regime. For the cases of VS and RE, numerical results do not exhibit significant difference in Re_c where it is found to be ∼2290 and ∼2090 respectively. To highlight the difference of Re_c amongst various inlet configurations, a comparison of experimental f_f is given in Fig. 5a. It can be clearly seen that the BM inlet shows the most delayed transition compared to rest of the three MCs. A potential explanation to the similar behavior has been provided by Tam et al. [19] where the smoother inlet was able to maintain the laminar state longer than other configurations by causing lower turbulent



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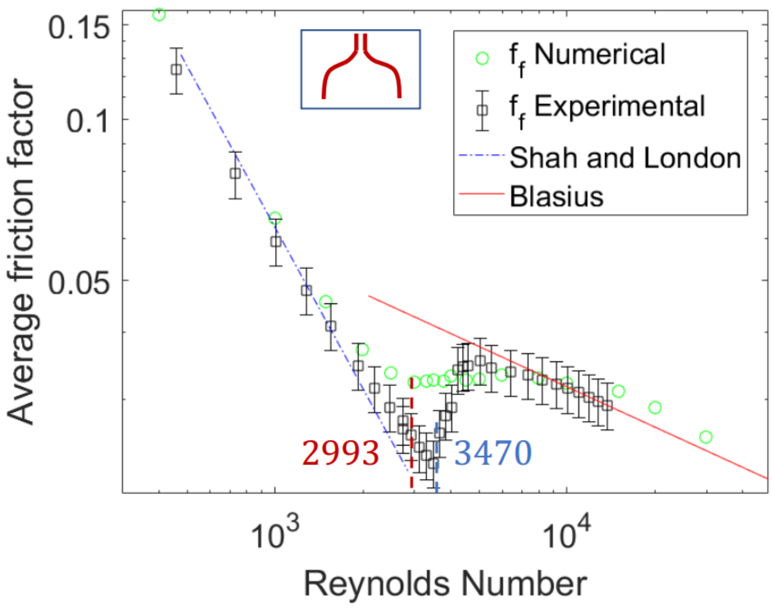
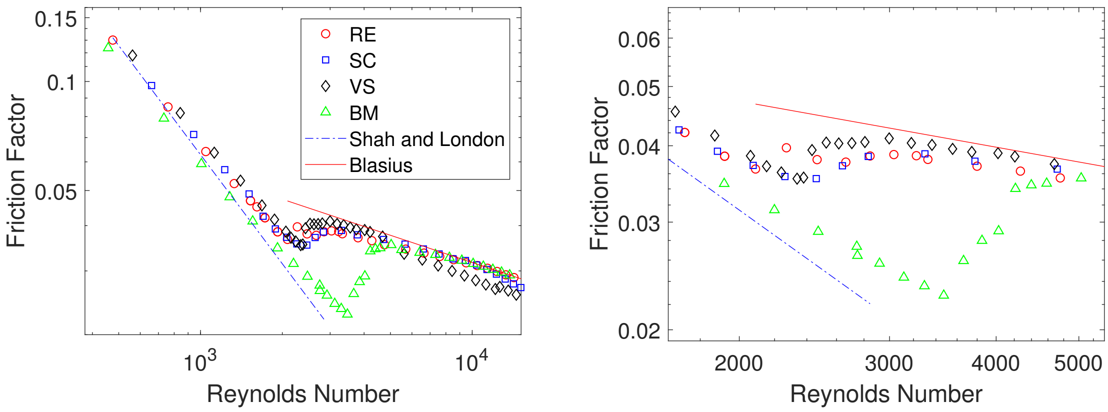


(b)

Figure 4: Friction factor for RE (**a**), and BM (**b**): blue and red vertical lines denote experimental and numerical Re_c respectively.

perturbations at MC inlet. By using $\gamma - Re_\theta$ transitional turbulence model, Minkowycz et. al [23] also showed that if the parabolic velocity profile is maintained at the channel inlet with $TI = 1\%$, an abrupt flow transition from the laminar to turbulent happens at the very high Re.

The other three MCs instead, do not show significant difference in Re_c amongst each other, and therefore to better observe the transition, a magnified region in the intermittent Re regime is also presented in 5b. Re_c evaluated from current experimental and numerical studies along with the relevant results from the literature are reported in Table 2.



(a) (b)

Figure 5: Comparison of f_f curves for all the tested inlet shapes to establish Re_c (**a**), and zoomed view in the range of $1500 < Re < 5000$ (**b**).

Table 2: Numerical and experimental Critical Reynolds number

Channel	Exp. Re_c	Num. Re_c	Tam [19]	Dirker [20]	Moruz [21]
RE	2090/2660	2360	-	-	-
V-shape	2340	2290	-	-	-
SC	2460	2780	3100	2000	3600
BM	3470	2993	5100	1800	3800

Experimental results show that MC with RE inlet seems to show two relative minimum points of friction factor in Moody Chart before becoming fully turbulent. Similar behaviour is confirmed by simulation results, even though the Reynolds number at which the minimum is observed in numerical f_f is much higher than experimental one. A mention of such experimental behavior can also be found in [20] where for BM inlet shape, authors observed two sudden changes of f_f curve before transitioning to fully turbulent flow. In order to establish the length of transitional regime (ΔRe_{LT}), the difference in Re between the onset of transition (Re_c) and when the flow reaches the fully turbulent condition i.e. slope of f_f parallel to Blasius law (Re_t), is used for all the four investigated inlet shapes and comparison is reported in Table 3. From both experimental and numerical results, it can be seen that the length of transitional regime is also higher for BM. This is followed by RE and SC. There exisits descripency between numerical and experimental results of VS where experimental results show somewhat abrupt transition whereas numerical results show smooth transition to fully turbulent flow.

Table 3: Numerical and experimental Re_c

Channel	Exp. Re_t	Exp. ΔRe_{LT}	Num. Re_t	Num. ΔRe_{LT}
Rounded Entrance	6644	4554	6881	4521
V-shape	4020	1680	6697	4407
Sudden Contraction	5660	3200	5956	3176
Bellmouth	9157	5687	9973	6980

5. CONCLUSIONS

Effect of inlet manifold shape on the laminar to turbulent flow transition using Nitrogen gas flow inside MCs is experimentally investigated. As observed by the other groups using incompressible fluids, flow transition is delayed the most using BM inlet shape. Similar findings are also found using a RANS $\gamma - Re_\theta$ transitional turbulence model. A maximum discrepancy of 13 % between experimental and numerically estimated Re_c is observed for a case with BM inlet shape. Experiments show that MCs with all the tested inlet manifold shapes attained the fully turbulent state in ΔRe_{LT} of ∼6000-7000 whereas for BM it is ∼10000. Current investigations have confirmed that even for compressible fluids inside MCs, inlet shape has relevant effects on the onset of laminar to turbulent flow transition.

ACKNOWLEDGEMENTS

This research received funding from the European Union's Framework Programme for Research and Innovation Horizon 2020 (2014–2020) under the Marie Sklodowska-Curie Grant Agreement No. 643095 (MIGRATE Project).

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