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Non-dimensionalization and mixing quantification of laminar twin semi-confined jets

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ABSTRACT

Two-dimensional laminar simulations of two parallel jets issuing into a semi-confined space were conducted. Critical Reynolds numbers were noted when the flows transitioned from a steady state symmetrical flow to the formation of secondary downstream recirculations and ultimately to transient flow. To better understand the characteristics of the flow, simulations were run at a fixed jet spacing with altered inlet sizes. It was found that using a momentum based Reynolds number instead of the standard volumetric flow method allowed better prediction of secondary downstream recirculations. However, when comparing simulations run with the same geometric setup, but with two different inlet velocity profiles, the Reynolds number based on flow rate is more consistent than the momentum based Reynolds number. A modified Reynolds number is proposed and tested across four jet spacings to determine the robustness of the new non-dimensionalization. Furthermore, a new method of quantifying and visualizing mixing is used to maximize mixing under varying jet spacings. It was seen that the majority of mixing occurred in the space between the two jets. Placing the jets along the walls of the confined space allowed for the most efficient mixing.

1. Introduction

A great deal of experimental work and Computational Fluid Dynamics (CFD) modeling has been conducted on the behavior of single jets issuing into confined spaces. Of interest in these studies is the natural instability of the flow. At a critical Reynolds number, the flow goes through a pitchfork bifurcation resulting in an asymmetric flow pattern regardless of the symmetry of the geometry.

Multiple studies have been conducted on how changing the expansion ratio affects the onset of the pitchfork bifurcation. Drikakis (1997), Alleborn et al. (1997), and Tsui and Wang (2008) all reported that decreasing the inlet size causes a decrease in the critical Reynolds number for onset of the pitchfork bifurcation. Wahba (2007) compared simulations using explicit and implicit solvers, but was only able to model the asymmetric stable solutions using an explicit solver. An implicit solver could be used to model unstable symmetric solutions beyond the critical pitchfork bifurcation Reynolds number. Fearn et al. (1990) compared experimental results with 2D CFD simulations. Experimental results showed a gradual transition into asymmetry, whereas CFD models went through an abrupt transition. Mishra and Jayaraman (2002) were able to model a similar gradual transition into asymmetry by using an asymmetric grid rather than a symmetric grid.

Extensive research has been done on the instability of single inlet sudden expansion flows. Mizushima and Shiotani (2000) did a weakly nonlinear stability analysis of flows with imperfect setups, i.e. with a slightly asymmetric model. They were able to correlate the onset of asymmetry well with results reported by Fearn et al. (1990). Rusak and Hawa (1999) also preformed stability analysis by introducing disturbances into the flow and were unable to trigger asymmetry in the flow below the critical Reynolds number, but were able to trigger it in cases above the critical Reynolds number. Hawa and Rusak (2001) returned to look at the instability of the pitchfork bifurcation and found aspects of the flow that reinforce stability and promote instabilities. They believe that the viscous dissipation by downstream convection of perturbations introduced by upstream disturbances stabilizes the flow. However as the Reynolds number is increased, or the inlet size reduced, the stabilizing effect is reduced.

The majority of the CFD simulations of confined single jets have been done using 2D models. Some researchers have looked at comparing results of 2D vs. 3D simulations, and also looked for 3D effects in experimental studies. Durst et al. (1974) reported that the 2D simulations are accurate representations up to the pitchfork bifurcation. When the flow becomes asymmetric, where one of the recirculation regions grows significantly, this larger recirculation

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Nomenclature

a	quarter channel height (m)	Re_J	momentum flux based Reynolds number
D	inlet size (m)	Re_{Da}	Reynolds number with square root Da length scale
Δt	simulation time step (s)	ρ	density (kg/m^3)
f	body force (N/m^3)	S	inlet spacing (m)
γ	expansion factor	T_{avg}	average temperature within 5m downstream of inlets (°C)
H	channel height (m)	T_o	initial temperature (°C)
J	momentum flux (N/m^2)	T_i	inlet temperature (°C)
μ	dynamic viscosity (kg/(s m))	τ_{ij}	viscous stress tensor
ν	kinematic viscosity (m^2/s)	U_{avg}	average inlet velocity (m/s)
θ	non-dimensional average temperature	u_i	ith component of velocity (m/s)
p	pressure (N/m^2)	Y_n	flow solution (u_i, p) at iteration n
Re	flow rate Reynolds number		

region shows 3D effects that can govern its size. Chedron et al. (1978), Durst et al. (1993), De Zilwa et al. (2000), and Patel and Drikakis (2006) noted these 3D effects are important in the triggering of transience.

Less research has been done on multiple jets issuing into a confined space. Foumeny et al. (1996) ran simulations of two and three jets. They altered the side boundary conditions to either be no slip (to model walls) or cyclic (to represent equally spaced jets on either side). It was found that using a cyclic boundary condition does not accurately model the jet on jet interaction. Soong and Tzeng (1998) modeled two jets issuing into a confined space. They found that at low Reynolds number the flows were symmetric although the closer the jets were to the walls the more they would redirect towards the walls. As the Reynolds number was increased, or the jet spacing was decreased, the jet flows started to lean towards one another forming a strong centralized flow. With the jets merging near the inlets, the flow often resulted in an asymmetric behavior similar to that of a single jet. As the Reynolds number was increased, the jets eventually became unsteady. It was found that the jet on jet interaction had a stronger influence on the onset of the Hopf bifurcation than wall effects did. Nahum and Seifert (2006) also performed numerical simulations and experiments of twin confined jets similar to those reported by Soong and Tzeng (1998). In their studies they looked at three models, varying inlet size and spacing, to determine which setups had the potential for improved mixing. It was found that increasing the inlet size increases the critical Reynolds number for the onset of instabilities.

The primary interest seen in the literature is in studying how varying geometries affect the onset of unstable behavior in symmetric confined flows. Through understanding when and how instabilities present themselves, it becomes possible to more easily optimize model designs and to maximize mixing. The goal of the present study is to determine a new robust non-dimensionalization and a better way to quantify and visualize mixing. Simulations were run modeling 2D symmetric twin jets issuing into a confined space. The domain used is shown in Fig. 1 where S denotes the jet spacing, D inlet size, H downstream channel size, and 'a' is a quarter of the channel height H:

I, II, III, IV, and V denote the varying grid resolution regions detailed in the grid independence study. Evenly spaced inlets, $S = 2a$, was used as the standard model in the current study. It was seen that 'a' offered cleaner correlations and is used frequently in this study in lieu of H to describe the channel height. The flow was given a stagnant initial condition and the inlet flow was introduced with a constant uniform profile unless otherwise noted. All walls were modeled as no slip except at the inlets. Flow was allowed to freely exit the right hand side of the domain where the border was given a zero pressure boundary condition.

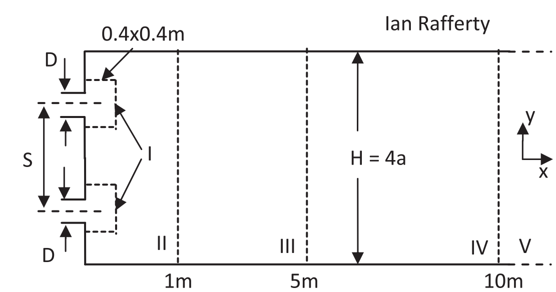

Fig. 1. The two dimensional solution domain and grid refinement regions (I–V) of two jets issuing into a confined space.

The initial Reynolds number used is based on the average inlet velocity and the inlet size shown in Eq. (1). The expansion factor is defined as the total inlet size divided by the downstream channel height shown in Eq. (2).

$$\mathrm{Re} = \frac{U_{avg}\rho D}{\mu} \quad (1)$$

$$\gamma = \frac{2D}{H} \quad (2)$$

Due to the large number of variables (spacing, expansion factor, Re, etc.) simulations were broken into four stages, each isolating specific areas of interest.

I. A mapping of critical Reynolds numbers across four jet spacings was initially conducted to form a general picture of the flow states under changing Re.
II. The effects of changing Re, expansion factor, channel height, and inlet velocity profiles were then observed around a single critical Reynolds number and constant jet spacing. A new non-dimensionalization for the Reynolds number and flow separation lengths was formulated to improve correlation.
III. The robustness of the new non-dimensionalizations was then proven by recompiling the mapping done in Stage I. Results were compared for three geometries with varying expansion factors and channel heights.
IV. Simulations were run at three jet spacings at a constant expansion ratio and channel height to highlight the effects of spacing on jet mixing.

2. Numerical validation

All simulations were run using PHASTA (Parallel (Sahni et al., 2009) Hierarchic Adaptive (Whiting and Jansen, 2001) Stabilized (Shakib and Hughes, 1991; Jansen et al., 2000) Transient Analysis),