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PULSATING FLOW AND HEAT TRANSFER IN A CHANNEL WITH SUDDEN EXPANSION

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Abstract. *Numerical investigations of pulsating laminar flow in a plane channel with sudden expansion have been carried out by solving 2D Navier-Stokes and energy equation for an incompressible fluid. Pulsation has been imposed on the axial velocity at the channel inlet. Results show an asymmetry in the flow and for certain amplitudes of pulsation the average wall Nusselt number can increase over the flow without pulsation.*

Keywords: *Pulsating flow, Heat transfer enhancement, CFD, Channel Flow*

1. INTRODUCTION

Flow field in a channel with sudden expansion, see Fig. 1, generally contains separation bubbles at the corner where heat transfer deteriorates.

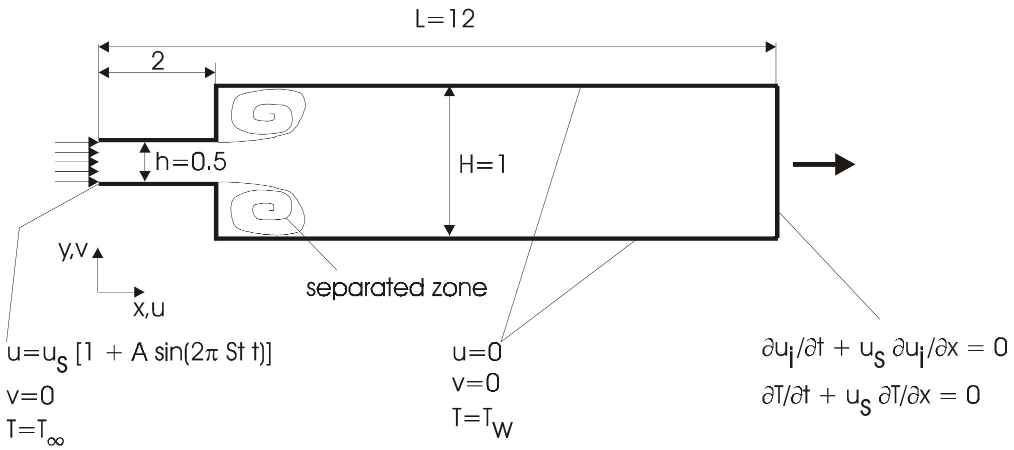

Figure 1 - Schematic of the geometry and the chosen boundary conditions.

Imposition of temporal oscillation on the flow at the channel inlet can dislodge these bubbles. Separation bubbles then should shed as transverse vortices with their axes parallel to the spanwise direction and may thereby influence the heat transfer by periodically mixing and sweeping the wall boundary layers. Pulsating laminar flow in a channel with uniform cross section was first studied by Richardson & Tyler (1929) who found the velocity overshoot and also backflow near the wall.

Siegel & Perlmutter (1962) found an overshoot in the temperature profile producing local peaks in heat transfer in pulsating channel flow. However, Ma et al. (1994) found from computational results in the Prandtl number (Pr) range of 100 and 12000 that average wall heat transfer in a pulsatile flow is practically the same as in a steady flow in the channel.

The laminar flow in a channel with uniform cross section may not be much influenced by pulsation. However, in a channel with sudden expansion one can expect substantial influence of the pulsation on the flow structure.

Valencia & Hinojosa (1997) conducted numerical investigations of pulsating flow and heat transfer characteristics downstream of a 2D backward-facing step. They reported that the primary vortex breaks down through one pulsatile cycle for an amplitude of oscillation of one and a Reynolds number Re of 100, referred to double upstream channel height, which causes an approximately 9% higher time-averaged heat transfer rate than with steady flow. They chose a sinusoidal variation of parabolic velocity profile at the inlet.

Sobey (1985) investigated symmetric and asymmetric 2D channel expansions experimentally and numerically. His work is focused on the effect of vortex waves, which are produced by oscillations, on fluid flow. He discussed asymptotic analysis of wavelike structures in the solution for steady flow through an asymmetric channel. It is argued that a vortex wave is a result of shear-layer instability.

A different approach was done by Al-Haddad & Al-Binally (1989) who derived an empirical correlation for prediction of heat transfer coefficient in a heating process for steady and pulsating flow of air through a rigid circular pipe. They defined a new dimensionless number composed of Re and dimensionless flow frequency. For critical numbers above $2.1\text{x}10^5$ a significant heat transfer enhancement is observable.

The purpose of this work is to investigate numerically laminar flow and temperature fields and to calculate heat transfer in a 2D channel with sudden expansion with an imposed sinusoidal pulsation on the inlet axial velocity.

2. BASIC EQUATIONS AND METHOD OF SOLUTION

The channel as shown in Fig. 1 has an 1:2 sudden expansion. The flow field is described by the 2D unsteady continuity, Navier-Stokes and energy equations in cartesian coordinates for a Newtonian, incompressible medium with constant properties. The basic equations in dimensionless form are

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_j}{\partial t} + \frac{(\partial u_j u_i)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{1}{\mathrm{Re}}\nabla^2 u_j, \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial (u_i T)}{\partial x_i} = \frac{1}{\mathrm{Re\,Pr}}\nabla^2 T. \tag{3}$$

The dissipation term in the energy equation, Eq. (3), is neglected, since the used Pr of the fluid is fixed at 0.71, which corresponds to air at 1 bar and 20°C. The computations have been performed using the nondimesionalized variables x=x*/H*, y=y*/H*, $u=u^*/u^*_s$, $v=v^*/u^*_s$, $p=(p^*-p_\infty)/\rho u^{*2}_s$, $t=t^*u^*_s/H^*$, $T=(T^*-T_\infty)/(T_w-T_\infty)$, Pr=μc/k and $Re=\rho u^*_s H^*/\mu$. The dimensional variables are denoted by asterisks. Further, x and y are the axial and normal coordinates, H* the width of the wider channel, u and v are the axial and radial velocity components, u^*_s the reference inlet velocity, p the pressure, t the time, T the fluid temperature, p_∞ and T_∞ are ambient pressure and temperature, T_w the wall temperature, μ the dynamic viscosity, k the thermal conductivity, ρ the density, and c the specific heat of the fluid.

No-slip condition on the solid surfaces is used. For steady case, the inlet velocities are u=1 and v=0. In case of pulsatile flow the radial velocity component is zero but the axial velocity component is modified to

$$u = u_s\left[1 + A \cdot \sin(2 \cdot \pi \cdot St \cdot t)\right] \tag{4}$$

where u_S is the velocity for steady case ($u_S=1$), A the amplitude of oscillation and $St = f^*H^*/u^*_S$ the Strouhal number which nondimensionalizes the frequency of pulsation f*. Furthermore, the inlet fluid temperature is maintained at $T_\infty=1$ with or without pulsation, the wall temperature T_W is 2.

The convective boundary conditions at the nominal outflow are:

$$\frac{\partial \vartheta}{\partial t} + u_s \frac{\partial \vartheta}{\partial x} = 0 \tag{5}$$

where ϑ = u, v, T. The chosen ratio between the length and the height of the investigated sudden expansion is L/H=12, and the length after the channel enlargement is 10 channel heights, so that the recirculation zones after the sudden enlargement are sufficiently upstream of the outlet.

The basic equations have been solved by a finite-volume procedure after SIMPLEC with co-located grid arrangement and momentum interpolation. Central difference discretization was used for the diffusive terms and flux-blending scheme was implemented for the convective terms which approaches a second-order accuracy with progressing solution of computation. The difference equations were solved by the strongly implicit procedure. Computation of the Nusselt number on the upper wall of a backward-facing step showed that grid independent results could be reached for Δx=Δy=0.033, Fig. 2. The time increment between two successive time steps was 0.01. Smaller time increment (t=0.005) did not give any significantly different result. The convergence criterion was the equality of the inlet mass flow and exit mass flow within 0.1%. The Computations were conducted on an IBM RISC workstation.

For each time step n during computation the Nusselt number Nu and the friction coefficient c_f are computed

$$Nu^n = \frac{-\frac{\partial T_n}{\partial y}\Big|_W H}{T_W - T_\infty} \tag{6}$$

$$c_f^n = \frac{\tau_W^n}{0.5 \rho u_S^{*2}} \tag{7}$$

with

$$\tau_W^n = \eta \frac{\partial u^n}{\partial y}\Big|_W \tag{8}$$

the wall shear stress. To have time integrated values of Nu and c_f their values are averaged over each time step.

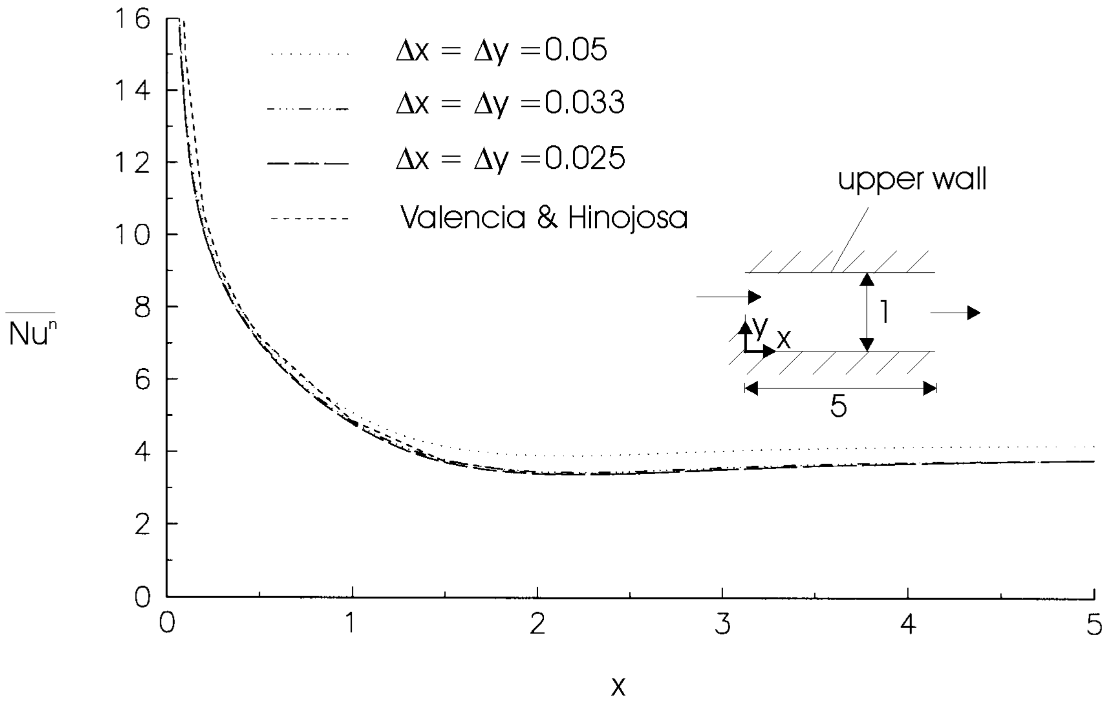

Figure 2 – Grid independence test: time-averaged Nusselt number vs. x direction for the upper wall of a backward-facing step.

3. RESULTS AND DISCUSSION

Figure 3 shows the axial velocity u against the time for the first almost 35 time units. The fluid at the inlet of the sudden expansion has a Re of 100. The chosen point at which the u velocity is detected is x=10.6 and y=0.5. This point lies in vicinity of the fluid outlet because we wanted to check whether the unsteadiness at the inlet is transferred through the whole geometry. Indeed, the effect of pulsation is remarkable through the sudden expansion, as seen in Fig. 3.

The first 24.86 time units, we computed steady flow until convergence, and the converged velocity u is 0.8. After imposing pulsation with St=1.0 and A=0.2 the velocity starts swinging sinusoidally around this value, beginning with a period of transition of four peaks. Observation of the time-dependent behavior of other parameters, like pressure p or radial velocity component v, yields similar plots. Furthermore, the plot shows that the chosen boundary conditions at the exit do not influence the imposed pulsation.

The vector plot in Fig. 4a shows a dynamic movement of the flow at every time increment. This dynamic flow behavior fits well to the observations of Ma et al. (1994) for sudden-expansion pipe flow. For $\omega t=0.2$ and 0.4 the flow is fully directed from left to right.

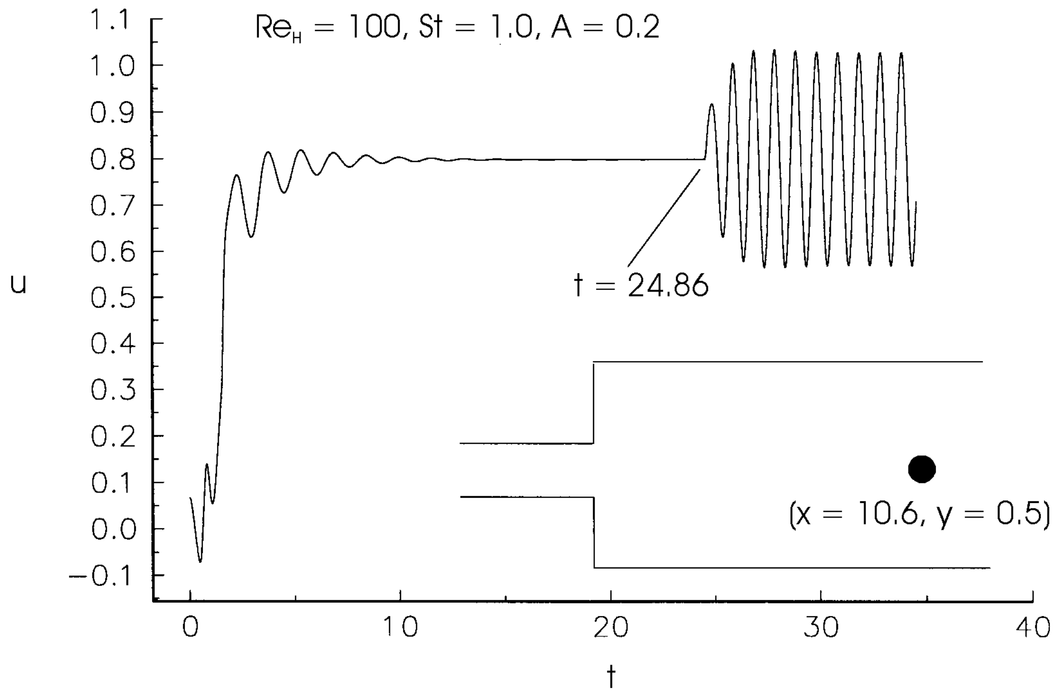

Figure 3 - Course of u velocity at x=10.6 and y=0.5 during computational iteration for $Re_H=100$ - onset of pulsation after t=24.86 with St=1.0 and A=0.2.

Backflow in the vicinity of the walls can be observed through the whole geometry for $\omega t=0.6$ but the core flow goes on streaming towards exit. Later, the region of backflow enlarges and even reaches the centerline.

The figure sequence illustrates that the recirculation bubbles at each side of the walls, which can be observed in case of steady flow, shed during pulsation in one cycle, and consequently, the boundary layers are washed out and rebuild themselves again.

In Fig. 4b isolines of temperature for $Re_H=400$, A=0.6 and St=1.0 are plotted. In general, the iso-temperature lines are symmetrical relating to the symmetry axis at y=0.5. The most conspicuous changes are in the neighbourhood of the channel expansion. Near the walls, the isolines have wave-like structures, while at the middle, concentrical constellations shine out. The isolines do not change with time as dynamically as the flow pattern in Fig. 4a, which is reported by Ma et al. (1994) as well.

Figure 5 presents the time-averaged Nusselt number $\overline{Nu^n}$ against the contour-fitted wall co-ordinate ζ for different amplitudes A and for $Re_H=100$ and the Strouhal number St=1.0. There are some small differences in the results of the upper and lower walls (lower wall values have not been shown). However, some enhancement over the steady flow Nu (A=0) can be observed.

Figure 6 shows the time-averaged Nu on the upper wall against the amplitude for $Re_H=100$. The behavior of Nu depends strongly on St and cannot be generalized.

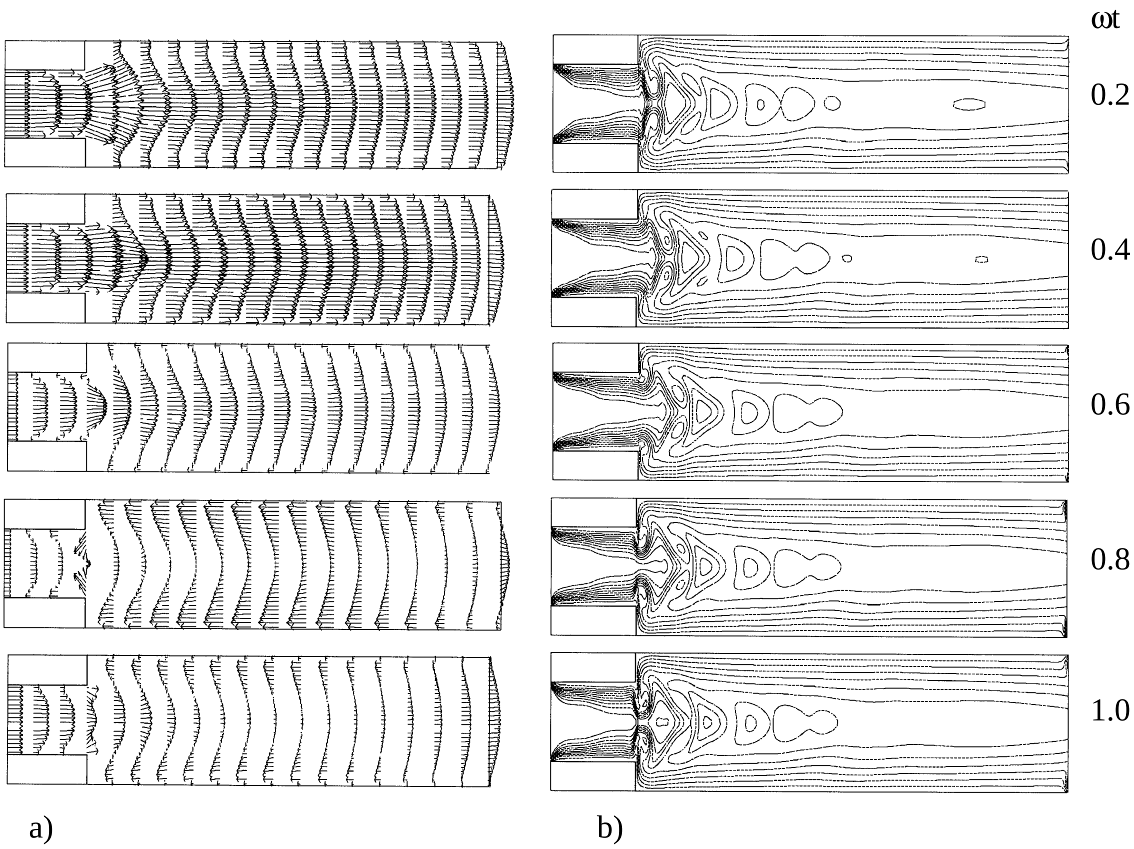

Figure 4 - Velocity plots (a) and isolines of temperature (b) during one cycle of pulsation in the 10^{th} period for Re=400, A=0.6, St=1.0 and ωt=0.2, 0.4, 0.6, 0.8, 1.0.

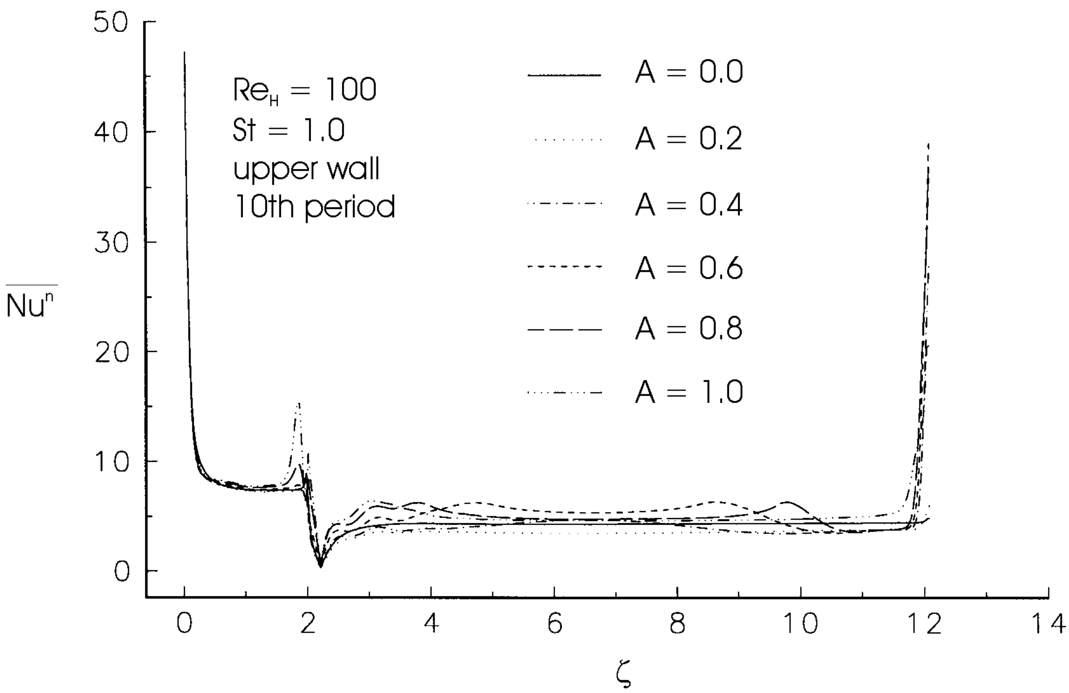

Figure 5 - Time-averaged Nusselt number of 10^{th} period vs. contour fitted wall co-ordinate ζ for the upper wall in dependence of amplitude A (St=1.0, Re_H=100).

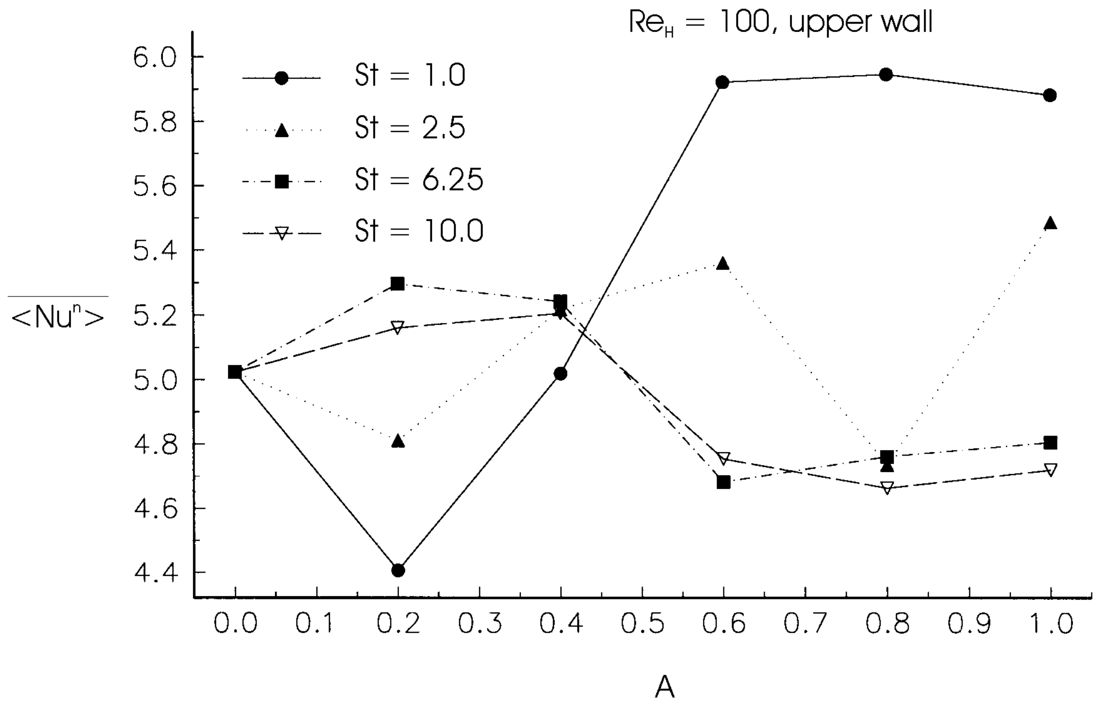

Figure 6 - Local and time-averaged Nusselt number vs. A for the upper wall with Re_H=100 - variation of Strouhal number St.

The results on the lower wall are nearly a mirror image of Fig. 6 and will not be shown. We notice a sharp increase in Nu as the amplitude increases from 0.2 to 0.6 for the case of St=1.0. The average Nu at A>0.4 are larger than that for steady flow.

4. CONCLUSION

The essential results are summarized here.

- Assumption of a symmetry line at y=0.5 is not realistic for pulsatile flow in a sudden expansion with an area ratio of 1:2 and a Re range between 100 and 900.
- For certain amplitudes and St, the local and time-averaged Nu differs between the lower and upper wall about 15% (lower wall values are not shown). For Re_H=100, these critical amplitudes decrease with increasing St. The discrete and systematic irregularities denote strong asymmetries in the flow pattern.
- The highest global heat transfer enhancement through pulsation for Re_H=100 is reached with St=1.0 and A=0.8 with Nu=5.971 in comparison to 5.025 for steady flow which corresponds to 18.8%.

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