NAG3-2422

AIAA

AIAA 2003-7016

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AIAA 12-th INTERNATIONAL SPACE PLANES AND HYPERSONIC SYSTEMS AND TECHNOLOGIES CONFERENCE
15-19 DECEMBER, 2003, NORFOLK, VIRGINIA, USA

Enhancement of Mixing and Heat Transfer By Corrugated Permeable Walls

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ABSTRACT

A re-circulation method that is based on the static pressure recovery in the divergent part of a converging-diverging flow channel is discussed. This method can be used to design a static device that can be used to increase the residence time of the fluid and the mixing in the transverse and/or flow directions in compressible and incompressible fluids flowing at subsonic velocities. The device with external reverse flow channels will produce mixing in both transverse and flow directions. If mixing in the flow direction is not desired, the concept can be used to design an insert to provide only transverse mixing.

Theoretical relationships for a re-circulating one-dimensional incompressible flow around a converging-diverging channel were obtained. Attempts at numerical simulation of re-circulation in compressible fluids were not successful. Qualitative experimental verification of re-circulating flows for incompressible and compressible fluids were obtained.

I. INTRODUCTION

The paper describes the re-circulation method that can be used to enhance the liquid phase heat and mass transfer in tubular devices and chemical reactors, in which the mainstream energy is used for re-circulation. The re-circulation method is based on the static pressure recovery in the divergent part of a converging-diverging flow channel. A mechanical energy balance on the divergent section of the channel shows that the static pressure at the throat is always higher than that in the downstream main tube. If one connects the downstream larger cross section region of this tube (with high pressure) to the smaller cross section region upstream (with low pressure) by a reverse flow channel, the fluid from downstream flows back upstream due to the pressure difference across the reverse flow channel.

The proposed re-circulation method can be used to design a static device, such as the one shown in Figure 1, that can be used to increase the residence time of the fluid and the mixing in the transverse and/or flow directions in compressible and incompressible fluids flowing at subsonic velocities. The increase in the residence time is achieved without any moving parts that will contribute additional

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capital and maintenance costs and decrease the reliability. The capital cost is expected to be significantly lower than the existing external re-circulation systems and the only additional operating cost will be the energy needed to compensate for the increase in the pressure drop due to the converging and diverging sections and, if external reverse-flow channels are used and the size of the flow conduit is kept constant, due to the increased flow as the result of re-circulation.

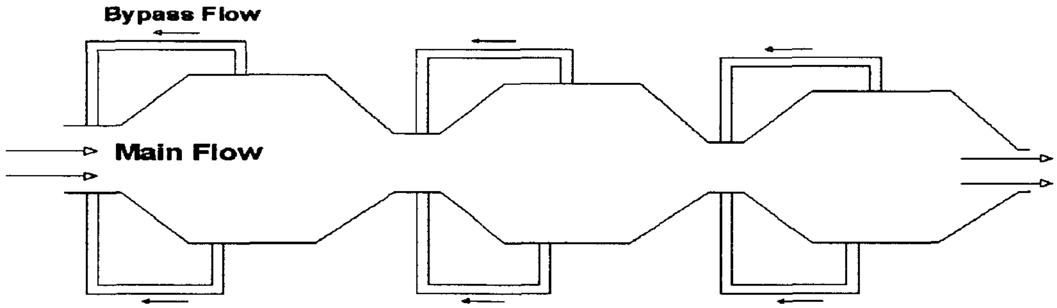

Figure 1. Basic re-circulation device with external reverse flow channels

The re-circulation method, when external reverse flow channels are used, enhances mixing in transverse and flow directions. This will result in an increase in the residence time of the material flowing through the equipment and will reduce the temperature and/or concentration gradients in the flow direction. The latter effect will decrease the transverse transport rates and thus, for some operations, may in part counteract the positive effects of transverse mixing. On the other hand, reduced temperature and concentration gradients in the flow and transverse directions will be very advantageous in equipment such as isothermal reactors for highly exothermic complex reactions in which the close control of temperature and concentration is extremely important due to rate, equilibrium, and selectivity considerations.

On the other hand, if mixing in the flow direction is not desired, the same concept can be used to create transverse mixing by using an insert as shown in Figure 2.

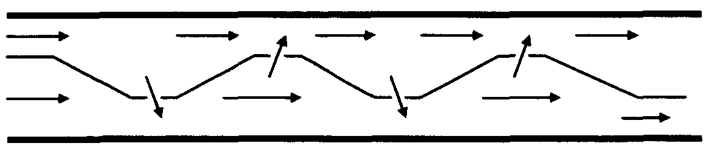

Figure 2. Basic re-circulation device with insert

When used in laminar flow, the device with an insert will provide controlled transverse mixing while eliminating reverse flow. This type of device is expected to find applications in laminar flow heat and mass transfer operations.

RELATIONSHIPS FOR ONE-DIMENSIONAL INCOMPRESSIBLE FLOW

A single unit of the basic device with external reverse flow channels is shown in Figure 3. Using the mechanical energy balance on the two control volumes, one between sections 1-1 and 2-2, and the other between 3-3 and 4-4, we can deduce the basic equations for the flow rate of the re-circulated fluid, the design parameters of the device, and the residence time of the fluid in the device.

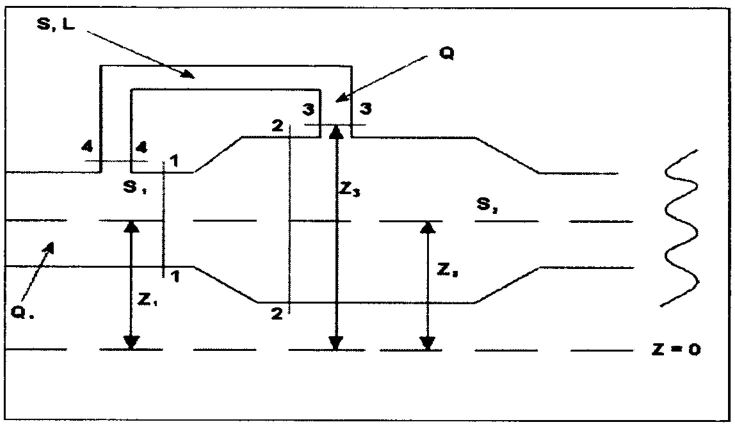

Figure 3. Re-circulation unit with an external reverse flow channel

With the following assumptions,

$\alpha_1=\alpha_2=\alpha$

$\rho_1=\rho_2=\rho_3=\rho_4=\rho$

$(P_2-P_1)=(P_3-P_4)$

$u_2S_2=u_1S_1=Q^*+Q$

we can obtain

$$(Z_1-Z_2)+\frac{(Q^*+Q)^2}{2\alpha g S_2^2}\left[\frac{S_2^2}{S_1^2}(1-K_e)-1\right]=(Z_4-Z_3)+\frac{1}{2\alpha}\frac{Q^2}{gS^2}\left[\frac{f_D L}{d}+K_3+K_4\right]\ .$$

Subscripts 1 and 2 refer to the small and large cross sections, respectively; S, L, and d are the cross-sectional area, length, and diameter (or equivalent diameter) of the reverse flow channel; Z_1 and Z_2 are the elevations of the pipe axis in the small and large cross sections; Z3 and Z4 are the elevations of the inlet and exit of the reverse flow channel; α is the ratio $(u_{ave})^3/(u^3)_{ave}$ assuming either laminar or turbulent flow at all cross sections considered; Q^* is the volumetric flow rate at the inlet upstream of the re-circulation section; Q is the volumetric flow rate in the reverse flow channel; K_e is the friction loss in terms of the number of velocity heads in the expanding section of the main channel (between sections 1-1 and 2-2); K_3, K_4 are the inlet and exit losses at sections 3-3 and 4-4, respectively; g is the gravitational acceleration; and F_D is the Darcy friction factor in the reverse flow channel.

For the case of negligible (Z_1-Z_2) and (Z_4-Z_3), a criterion for the existence of reverse flow can be obtained:

The static pressure recovery is easily explained by Bernoulli's equation. Bernoulli's equation describes flows

$$\frac{S_2^2}{S_1^2}(1-K_e)-1>0$$

For an expansion angle $\theta<50°$,

$$K_e = \sin\theta\ (1-\frac{S_1}{S_2})^2 \quad .$$

The above equations can be used to establish a constraint on the design of the re-circulation device:

$$\sin\theta\left(1-\frac{S_1}{S_2}\right)^2 < 1-\frac{S_1^2}{S_2^2}$$

With the same assumptions the volumetric flow rate in the reverse flow channel is given by:

$$Q=\frac{Q^*}{\frac{S_2}{S}\left[\frac{f_D L/d+K_3+K_4}{\left(S_2^2/S_1^2\right)\left(1-K_e\right)-1}\right]^{1/2}-1}$$

FLOW SIMULATIONS

To further examine the re-circulation concept several numerical simulations were conducted using Navier-Stokes (NSE) and Euler analysis of the subsonic flow of a compressible fluid in a smooth shaped divergent-convergent (sinusoidal) nozzle with a single round loop. The flow is produced by a pressure difference at the nozzle inlet and exit. The NASA CFL3D and Vulcan numerical codes were employed on structured multi-grids developed using GRIDGEN software, versions 9 and 13. The preliminary numerical simulation results were not successful in demonstrating the existence of reverse flow for low speed gas flow inside a traditional 2D convergent-divergent nozzle or variable 2D channel with a reverse flow channel. Details can be found in reference [1].

EXPERIMENTAL TEST RESULTS

Compressible Flow Tests: Experimental tests were conducted in the Hampton University low speed wind tunnel using a specially manufactured plastic model of an axisymmetric convergent-divergent nozzle with 2.54-cm throat diameter. The nozzle has a conical divergent section, with 10^{o} expansion angle and 2.62-cm exit diameter. A section of 1.27-cm internal diameter clear plastic tube serves as the horizontal reverse flow channel (Figure 4). Several strings were installed inside the reverse flow tube to indicate the flow direction. Pressure taps connected to a multi-manometer are used to obtain the static pressure distribution along the nozzle and in the reverse flow tube. Pitot tubes are used to measure the dynamic pressure on the nozzle centerline. The air flow is generated by a blower placed downstream of the test section. Figure 4 presents the picture of the reverse flow tube during a test run. The orientation of the threads during the test clearly show the presence of reverse flow.

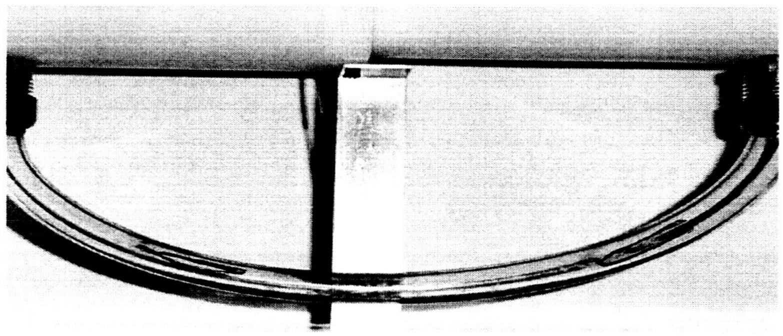

Figure 4. Demonstration of reverse flow for compressible flow

Water Flow Tests: Several experimental tests were conducted using a modified venturi meter. The Venturi meter has a throat diameter of 0.625 in (1.59 cm) and expands into a pipe with an internal diameter of 1.025 in (2.60 cm). The pressure taps on the Venturi meter were connected by a section of transparent plastic tubing to provide a channel for reverse flow. The experiments were run only at one water flow rate, which provided a velocity of 0.9 m/s at the throat and 0.33 m/s in the main pipe without the reverse flow channel. These correspond to a Reynolds number of 14,000 at the throat and 8,700 in the pipe indicating the presence of turbulent flow in the test section. Since the objective of these preliminary tests was to qualitatively demonstrate the existence of reverse flow in the re-circulation channel, forward and reverse flow rates could not be measured. To demonstrate the existence of reverse flow, a dye is injected by a syringe at the inlet of the reverse flow channel located at the downstream pressure tap of the Venturi meter. The dye patterns in Figure6 clearly indicate the existence of a substantial amount of reverse flow. The rapid mixing of dye with water in the reverse flow tube implies that the flow in this channel is also turbulent.

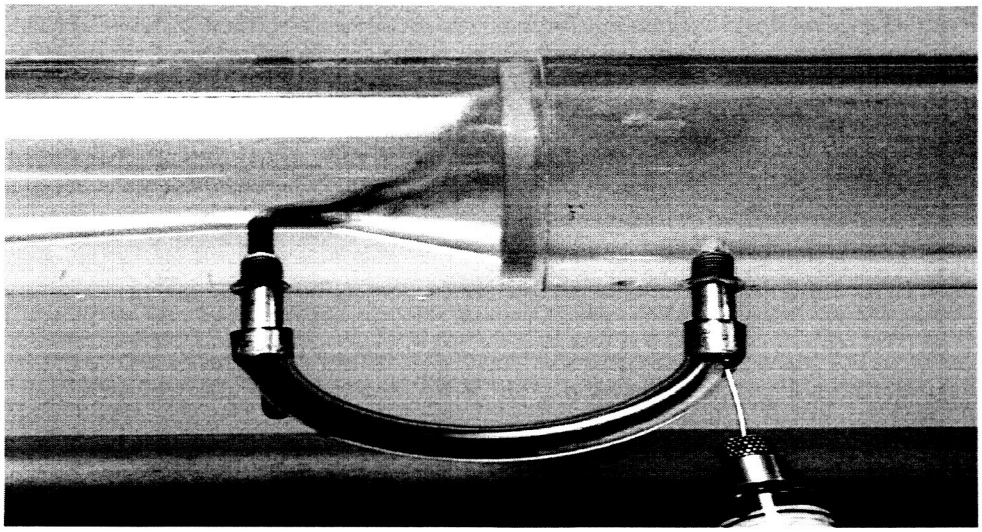

Figure 6. Demonstration of reverse flow in incompressible flow

Experimental Verification of Transverse Mixing in Re-circulation Devices with Insert: A new experimental setup was designed and constructed to demonstrate the transverse mixing in devices with insert. Mixing of hot and cold water will be used for this purpose. The setup is shown schematically in Figure 7.

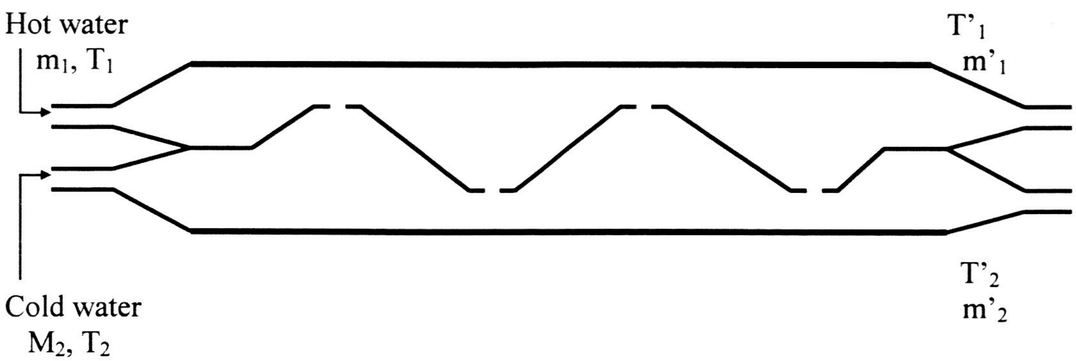

Figure 7. Experimental setup for the demonstration of transverse mixing

Material and energy balances around the experimental unit gives an expression for the exit temperature for perfect mixing:

$$[T']_{ave} = [m'_1(T'_1 - T'_2) - (m_1 + m_2)T'_2]/(m_1 + m_2)$$

We can define a degree of mixing, d_m, based on this temperature for each section:

$d_{m,1}= (T_1 - T'_1)/(T_1- [T^1]_{ave})$

$d_{m,2}= (T_2 - T'_2)/(T_2- [T']_{ave})$

These in turn, can be used to optimize the device parameters for maximum transverse mixing.

CONCLUSIONS

Theoretical relationships for a re-circulating one-dimensional incompressible flow around a converging-diverging channel were obtained. Attempts at numerical simulation of re-circulation in compressible fluids were not successful. Qualitative experimental verification of re-circulating flows for incompressible and compressible fluids was obtained.

A new liquid-phase test setup was designed and is being constructed to investigate the transverse mixing that will be induced by an insert. Simultaneously attempts are underway to simulate the flow in this channel using commercial software. Future work will include experimental tests for liquid flows inside 2D and axisymmetric conduits with external reverse flow channels in order to obtain data on re-circulation in such systems. Also, we plan to experimentally investigate mixing, heat transfer and chemical reaction enhancement using the described approach.

ACKNOWLEDGEMENT

We would like to acknowledge the NASA Glenn and Langley Research Centers, especially Dr. Dennis M. Bushnell for interest and support to our research. This Research was partially conducted under the NASA grant NCC-3-1037.

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