A NEW ENTHALPY MIXING MEASUREMENT TECHNIQUE FOR FUEL ELEMENT DESIGN

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ABSTRACT

A new thermal tracing technique for the direct measurement of enthalpy mixing between coupled subchannels is presented. This technique is particularly suited for the performance evaluation of mixing promoters. The method is simple and versatile, being capable of implementation on compact and heterogeneos bundles like CANDU fuel element, using water high flows. Different mixing promoters like buttons and mixing vane were measured on a triangular array bundle with a relation of pitch to diameter of 1.26 at 8.5×10^4 Reynolds number.

INTRODUCTION

One of the main design factors in nuclear fuel elements is the thermohydraulic aspect. On these, the heating surface is composed of bundles of parallel rods that are refrigerated by interconnected fluid subchannels. In the particular case of CANDU fuel element designs, we find an heterogeneous and compact array of fuel rods and heating powers, giving more distributed subchannel enthalpies, in relation with the PWR fuel elements. For these reasons, the study of the thermohydraulic performance of the fuel element is more complex in the CANDU types than in the PWR ones.

A way to analyze this is solving the one dimensional conservation equations of heat, mass and moment on each subchannel. Examples of this approach can be found in the numerical codes (ASSERT, COBRA, etc.) used at the present for nuclear fuel elements thermalhydraulic design and evaluation. However to perform this kind of analysis the value of the mass, momentum and energy exchange between subchannel has to be known beforehand. Unfortunately up today the experimental methods available for mixing measurement have serious limitations.

At the present one approach has been to perform temperature measurements with real scale fuel bundle models, electrically heated (Forman, 1997). In this way general information of the fuel element performance (rod surface temperatures, dryout, critical heat flux, etc.) can be obtained. These tests have been performed on new geometries (an example is the work of Dimmick et al, 1999) and is systems including different appendages (McDonald, 1985). This kind of tests need large facilities, are very time consuming, and give only global information, so mixing rates can only be inferred approximately form the results.

Mixing rates can be measured using chemical traces, particularly suited for two-phase flows (Saddatomi et al, 1995), but to have good concentration measurements it is necessary to isolate the incoming and out coming flows from each subchannel, therefore limiting their use to very simple geometries. On the other hand, in one-phase flows measurements can be done with great detail and precision using either Laser Doppler Anemometry or Thermal Anemometry. Both methods have been widely used in the study of flows past rod-bundles (Renksizbulut, 1986; Wu, 1994), giving local information about velocities and turbulence components. Lased Doppler Anemometry can be used provided a good optical access is available to the area of interest, so its use in irregular geometries and in presence of local mixing elements (vanes, buttons) is complicated. Thermal anemometry usually involves the use of large test sections due to the relatively large size of the probes. Besides probes for use in water flows have poor durability (hot films), therefore most experiments are performed using filtered air as fluid. Another limitation is that thermal anemometry is difficult to apply to local mixing appendage measurements.

Therefore, the lack of proper data on mixing promoters performance is a serious drawback for the design of new bundle fuel elements that tend to take advantage of the improved mixing, widely implemented in PWR fuel elements.

In the present work a novel experimental technique for the measurement of mixing rates is presented. As we will show this technique provides important advantages over the methods used at the moment. Our approach was, in an adiabatic flow, to generate a thermal trace in only one subchannel through the use of superficial (low intrusively) heaters mounted on the rods, and to measure the decay of the thermal gradient originated between the neighbor subchannels involved.

The advantages of this setup are: the direct measurement of true thermal mixing, the use of real-scale models with real-scale roughness, materials, vibration behavior, etc., and the flexibility to measure in compact and heterogeneous geometries, even in presence of localized components, as separators, mixing appendages, etc.

EXPERIMENTAL METHOD

Thermal Method Procedure. The proposed technique consist on the introduction of a thermal trace in one subchannel and the measurement of its evolution downstream. For the particular case of two subchannels (*i* , *j*) connected by one gap, that interchange a turbulent mixing flow per unit length *w'*, we can write the energy balance for the subchannel *i* as follows:

$$\frac{d\left(A_i U_i \rho_i H_i\right)}{dz} = w'\left(H_j - H_i\right) + q'_i \qquad (1)$$

where A_i, , U_i, ρ_i, and q'_i, are respectively the cross section, mean axial velocity, density and heat input per unit length to subchannel *i* , and where *H* refers to each *(i, j)* subchannel enthalpy. Taking $w_i = A_i U_i \rho_i$ and subtracting the energy balance equations (1) for both subchannels, we obtain the following expression:

$$\frac{d\left(H_i - H_j\right)}{dz} = -w'\left(\frac{1}{w_i} + \frac{1}{w_j}\right)\left(H_i - H_j\right) + \left(\frac{q'_i}{w_i} - \frac{q'_j}{w_j}\right) \qquad (2)$$

In an adiabatic system with neglectable viscous dissipation ($q_i = q_j = 0$) and for a thermal and hydraulically developed flow (uniform w'), these differential equations can be solved for the temperature difference between both subchannels:

$$\Delta T(z) = \Delta T(z=0) \times \exp\left(-\frac{w'}{\rho}\mathrm{X}\right) \tag{3}$$

where $\Delta T=(H_i-H_j)/c$, being c the heat capacity of fluid, and $X=(1/w_i + 1/w_j)$ can be calculated with good accuracy from the test section flow. Hence, by the measurement of the temperature difference between both subchannels for several axial positions, we can determine the turbulent mixing w' value.

The mixing effect of mixing promoters can be considered, following the previous scheme, as a local mass and enthalpy interchange. In order to obtain this local parameter, we take two exponential decays that fit the behavior upward and downward the appendage position respectively. Assuming a local mixing w_l the temperature jump $(\Delta T_i - \Delta T_o)$ at the mixing promoter position can be obtained:

$$\Delta T_i - \Delta T_o = -\Delta T_i \; w_l \left(\frac{1}{w_1} + \frac{1}{w_2}\right) \tag{4}$$

This equation allow us obtain a expression for w_l

$$w_l = \frac{\Delta T_i - \Delta T_o}{\Delta T_i}\left(\frac{1}{w_1} + \frac{1}{w_2}\right)^{-1} \tag{5}$$

The application of this thermal tracing technique to a particular subchannel system requires local heaters providing very high heat fluxes without local boiling to introduce a measurable thermal trace to one subchannel, and a measurement instrument sensible enough to measure the trace decay in that subchannel and also the trace increment in neighbor subchannels. Both, heaters and sensing system, with these features required a careful development and are described in previous works of Silin et al. (2000, 2003a and 2003b).

Heaters. Heaters composed of a nickel alloy strap electrochemically deposited on a ceramic substrate were developed to generate the thermal traces. The ceramic substrate was chosen for its resistance to temperature, low thermal conductivity and for being a good substrate for the nickel deposition. The nickel alloy selected is highly resistant to corrosion, which makes it possible to use unfiltered tap water as fluid. At the ends of the ceramic tube two brass terminals were soldered, providing a good electrical contact as well as mechanical support. The heat flux used was 5x10^{5} W/m2.

Temperature Sensors. Temperature measurements were performed using two high thermal stability current sources similar to those described by Peattie (1987) and using platinum resistance thermometers (PT100) of 1mm section diameter. The tension signal was amplified using two programmable gain instrumentation amplifiers. To reduce self-heating but still keeping a good signal to noise ratio a 0.8mA current was adopted for both sensors. In this condition the self-heating variations in the measurement range was well within 1mK. In the electronics high thermal stability resistors and ultra low offset drift bipolar operational amplifiers were employed. The circuit thermal stability was verified, being the thermal drift lower than 2mK/K. During the measurements the circuit output was acquired by means of a PC with a 12bit analog to digital converter module.

The value to measure is the temperature increase from the test section inlet to different points at the test section, downstream of the heaters. To obtain this difference within the required precision, the second sensor downstream of the heaters, was calibrated against the first sensor at the test section inlet. Measurements of the background temperature profile with no heating power are done to compensate viscous heating effects.

Experimental Setup. To test the method a simple geometry shown in Figure 1 of three rods inside a circular tube was chosen. This geometry lets us make use of a complete three heater set, as would be used in a full-scale fuel element measurement, while preserving a simple data analysis. The gap to diameter relation of the test section is 0.26 and the wall gap to diameter is 0.09; hydraulic diameters of the subchannels are similar being 7.5mm for the central subchannel and 6.8mm for the external ones.

The test section (Silin et al. 2003b) was built with an acrylic tube and three high precision stainless steel rods. The general tolerances of the test section are about 0.2mm, the same order of magnitude of nuclear fuel elements manufacturing tolerances.

Power provided by heaters was measured based on the power provided by the direct current power sources. Connection and cable loses are smaller than 5%, and the current ripple was lower than 1.5% with a frequency of 50Hz; smaller components were found with a frequency of 150Hz. The stability of the output power during the measurements was within 3%.

The measurement sequence was as follows. Once the water circuit had stabilized at the desired flow rate and at 41 ± 1 °C, heaters were connected, current was applied and voltage measured. Temperature measurements were performed for various transversal positions and applied current and voltage values were measured again. Heaters and pump were turned off, the second sensor transversing mechanism was moved to a new axial position and the sequence was repeated.

RESULTS

All the measurements were performed at Reynolds number 85,000 calculated on the overall test section hydraulic diameter (6.9mm). The measurement of temperature was particularly sensible so care was taken to give sensors enough warm-up time to achieve repeatability within 3mK. Also averaging times were taken long enough to assure this precision. As the calculations are based on the assumption of 120° symmetry the temperature of the three peripheral subchannels is compared in each measurement to assure this condition. In the measurements performed the temperatures of the three subchannels resulted equal within a 15% for a mounting precision of 0.2mm for the rod azimuthal position and the tube inner diameter.

The values of temperatures measured in the central and peripheral subchannels for the bare bundle are shown in Figure 2. In this figure the temperature difference between the central and peripheral subchannels is shown. This measurement was used as reference for the performance evaluation of the mixing promoters tested. For this geometry the mixing ratio w' is 0.47kg/sm and the gap Stanton number St_g is 0.0074.

In this work we present three mixing promoters: buttons, the mixing vanes, and the flat spacers (Figure 3). The flat spacer is a metal sheet element similar to the mixing vane element but completely flat and is presented as a reference for evaluating the effect of the vanes.

The measurements corresponding to the three different mixing promoters are shown in Figure 4. The mixing promoters were located at 250mm downstream from the heaters end. It can be seen Buttons and Mixing vanes have a dramatic effect on mixing while the spacer has a much smaller mixing effect.

As the measurements are performed at two radial positions, one on the center of the central subchannel and the other on the peripheral subchannel they are representative of the subchannel mean temperature (Silin, 2003b) only if the temperature profile is completely developed. As can be seen in Figure 5 the temperature profile after the mixing vane (z =325mm) is distorted from the developed profile (z=125mm). We can also see that at z =625mm the temperature profile recovers its original appearance and the effect of the mixing vane is presumably extinct. In Figure 6 we can see the same profiles for the buttons, similar conclusions can be made for this case. It is clear therefore that temperature measurement immediately after the mixing promoters are not representative of the subchannels mean temperatures.

The mixing introduced by the mixing promoters was calculated as if it was concentrated on the mixing promoter location with a bare-rod mixing rate thereafter. The temperature evolution before and after the enhanced mixing region was extrapolated to z =250mm as shown in Figures 7, 8 and 9, and then the local mixing calculated based on equation 5. The results are shown on Table 1.

When considering the use of a mixing promoter in a fuel element, pressure drop needs also to be considered. The pressure head loss along the axial direction through the test section for the different mixing promoters is shown in Figure 10. The pressure loss due to the mixing promoters is estimated as the difference between the values of the bare-rod case and the mixing promoter case at z =525mm. The values calculated for each mixing promoter are shown in Table 1.

It can be seen that for the buttons setting and the mixing vane design considered the extra mixing achieved is similar, having the button design a lower pressure drop. Considering the use of these mixing vanes where a spacer already exists, the increased pressure drop due to the vanes themselves, that is the difference between the spacer case and the mixing vane case, is similar to the case of the buttons.

CONCLUSIONS

A novel thermal trace technique for the measurement of mixing between subchannels is introduced. Due to its simplicity, versatility and low cost we consider this technique highly useful for nuclear fuel design and assessment.

Measurements of mixing between subchannels with different mixing promoters are presented showing the ample potential of the method for mixing measurements under diverse conditions.

Due to the precision achievable, the method has the capability of measuring mixing variations due to geometrical or mounting tolerances. This could allow the experimental characterization of mixing behavior margins of commercial components of nuclear fuel elements.

References

1. Dimmick, G.R., Inch, W.W., Jun, J.S., Suk, H.C., Hadaller, G.I., Fortman, R.A., Hayes, R.C., 1999. "Full scale water CHF testing on the Canflex bundle". 6th Int. Conf. on CANDU Fuel, Ontario Canada, sept. 26-30.
2. Fortman, R.A., Hadaller, G.I., Stern, F., Midvidy, W.I., 1997. "Heat transfer studies with CANDU fuel simulators". 5th International Confeence on Nuclear Engineering May 26-30, Nice France 2428.
3. Macdonald, I.P.L., 1985. "Enhancement of Critical Heat Flux in Candu 37-Element Bundles". Canadian Nuclear Society 6th annual conference, Ottawa, pp 13.16-13.23.
4. Peattie, R., 1987. "A simple low-drift circuit for measuring temperatures in fluids". J. Phys. E: Sci. Instrum. 20565-567.
5. Renksizbulut, M., Hadaller, G.I., 1986. "An experimental study of turbulent flow through a squre-array rod bundle". Nucl. Eng. Des. 91, 41-55.
6. Sadatomi, M., Kawahara, A., Sato, Y., 1995. "Turbulent mixing of both gas and liquid phases between subchannels in two-phase hydrodynamic equilibrium flows". Celata, Shah (Eds.), Proc. Int. Symp. Two-Phase Flow Modelling and Experimentation, Rome , Vol. 1, pp. 403-409
7. Silin, N., Barbero, J., Bubach, E., Juanicó, L., 2000. "Medicion de mezclado entre subcanales combustibles: Desarrollo de una nueva técnica experimental". XXVII Annual meeting of the AATN, Buenos Aires, Argentina.
8. Silin, N, Juanicó, L., Delmastro, D., 2003a. "A thermal tracing technique" Latin American Applied Research Physic., in press.
9. Silin, N, Juanicó, L., Delmastro, D., 2003b. "Thermal mixing between subchannels: measurement method and applications". Journal of Nuclear Eng. and Design, in press.
10. Wu, X., Trupp, A.C., 1994. "Spectral measurements and mixing correlations in simulated rod bundle subchannels" Int.J.Heat Mass Transfer 37-8, 1277-1281.

Table 1

	Spacer	Mixing Vanes	Buttons
$(\Delta T_i\text{-}\Delta T_o)/\ \Delta T_i$	0.17	0.44	0.45
w_l [kg/s]	0.04	0.10	0.10
ΔP[kPa]	4.5	9.6	5.7

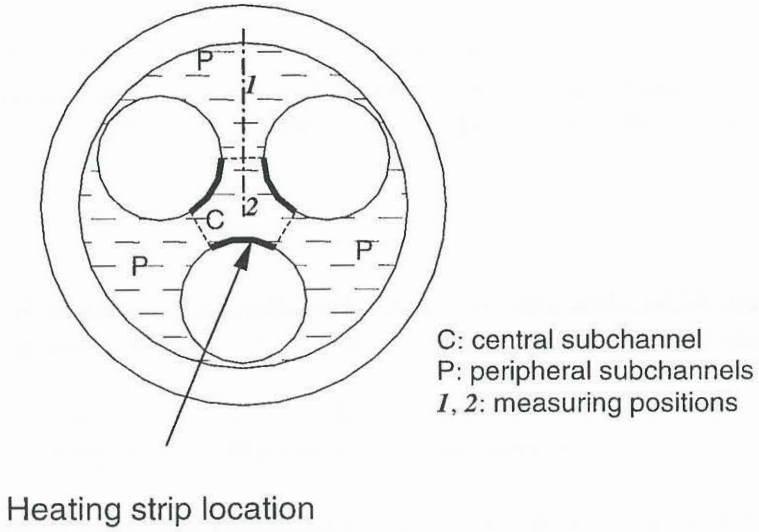

Figure 1: Test section geometry.

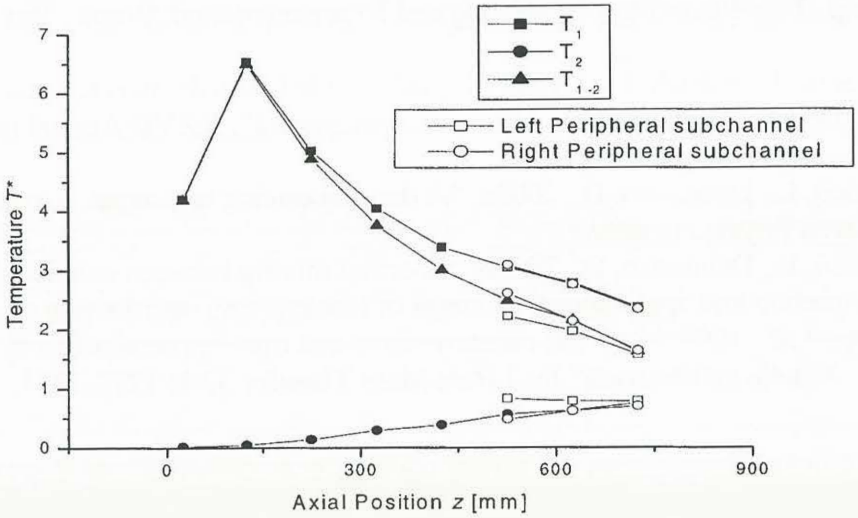

Figure 2 Temperature evolutions at points *1* and *2* and its difference.

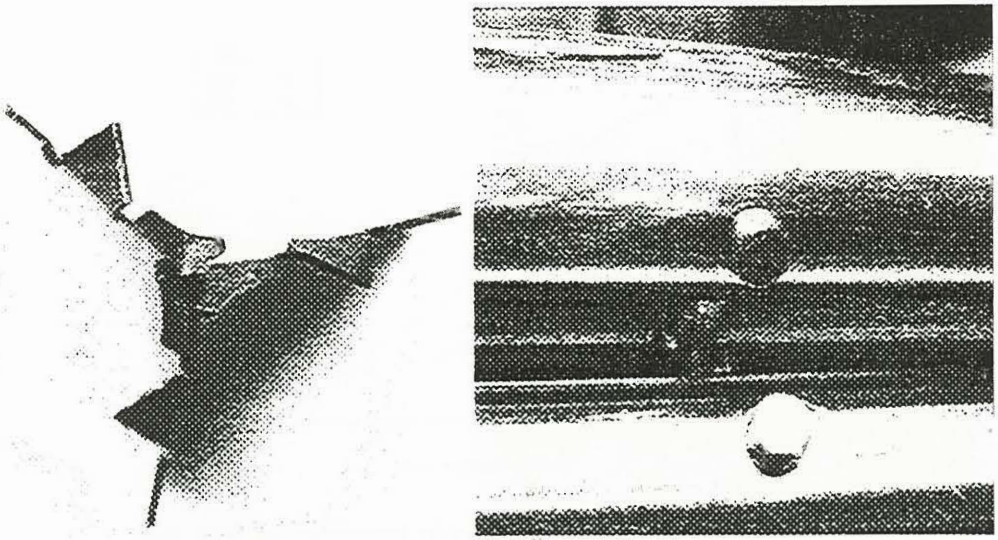

Figure 3 Mixing vanes and buttons.

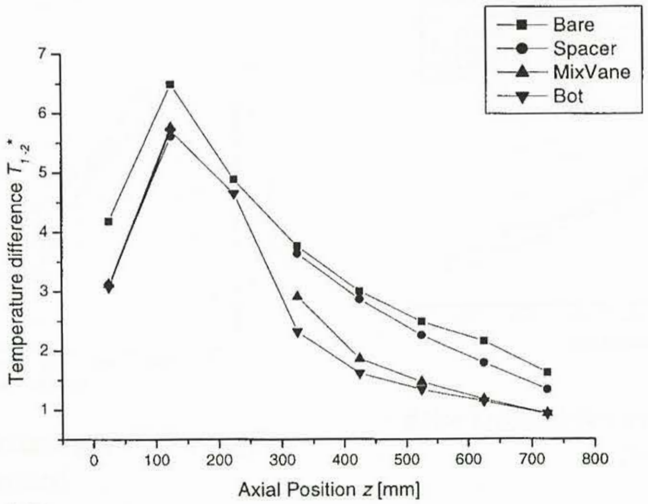

Figure 4 Temperature gradient decay with mixing promoters.

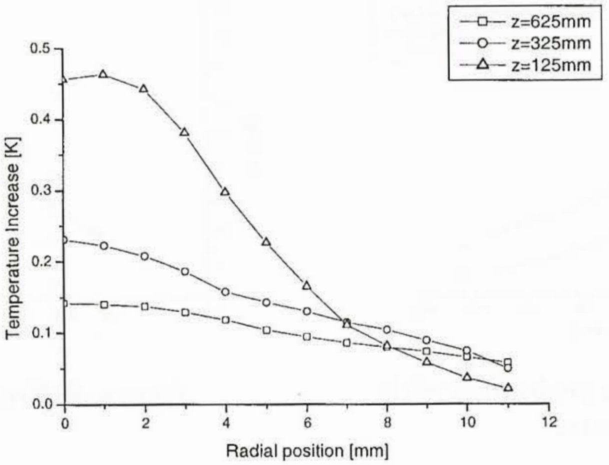

Figure 5 Temperature profiles in presence of a mixing vane.

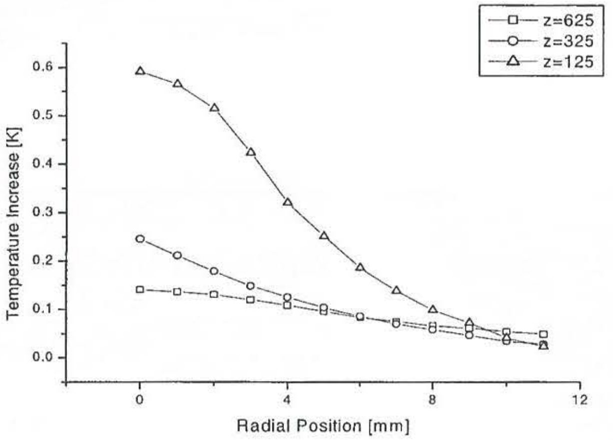

Figure 6 Temperature profiles in presence of buttons.

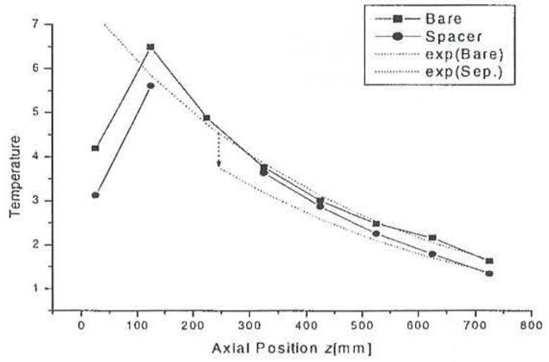

Figure 7 Temperature evolutions with spacer.

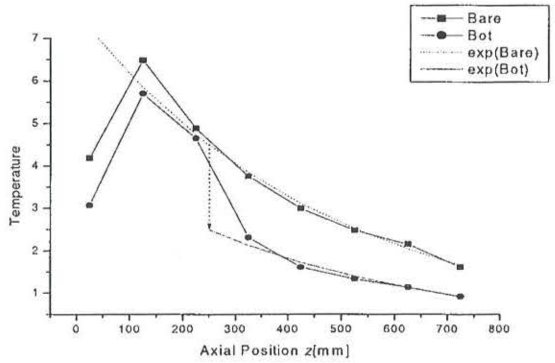

Figure 9 Temperature evolutions with buttons.

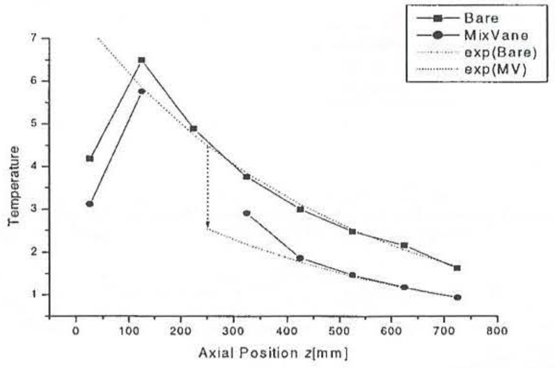

Figure 8 Temperature evolutions with mixing vane.

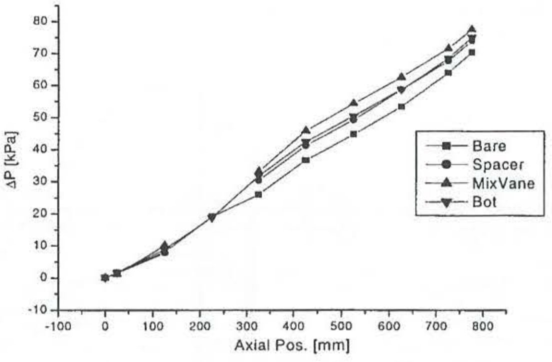

Figure 10 Pressure head loss