NOTES

A THERMAL TRACING TECHNIQUE

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***Abstract* --- A new thermal trace method is developed and tested in a water loop. Different measurements have been carried out to map the tracer concentration at a selected cross section downstream from the trace input location. Also bulk temperature increase was measured showing good agreement with the values calculated by energy balance. The method proposed gave meaningful information about the flow, opening the possibility of its application to the measurement of mixing rates between connected subchannels.**

***Keywords*--- thermal trace, water flow, mixing rate**

I. INTRODUCTION

Most nuclear reactors are fueled by assemblies of parallel fuel rods called fuel elements (FEs). The FEs are cooled by refrigerant flowing axially within the interconnected spaces between the fuel rods (subchannels). The thermal-hydraulic safety margin and the operation limits are often defined using computer codes that state conservation of mass, energy and momentum in each subchannel and implemented trough computer codes (COBRA, ASSERT, VIPRE). These codes require that the mixing rate between coupled subchannels, or a suitable correlation in terms of subchannel parameters, be known beforehand and provided to the code.

It has been shown that the mixing rates between subchannels connected by narrow gaps, as it is often the case, are dominated by large-scale, cuasi-periodic coherent structures (Hooper and Rehme, 1984). For this reason numerical simulations involving simple isotropic turbulence models do not provide realistic mixing rates, being necessary to perform expensive tests in sophisticated thermo-hydraulic facilities for each new FE design.

A variety of tracers have been used in flow study in order to have an insight of the transport mechanisms and, in confined or sub-channel flow, to quantify mixing rates (Bell and Le Torneau, 1960, Renksizbulut and Hadaller, 1986, Tong and Weisman, 1996, Kawahara *et al.*,1997).

Flow visualization in gas flows, particularly for aerodynamic studies, is achieved using different fumes. Ink, electrolitically generated gas bubbles, different solid particles, etc., have been largely used for the same purpose in water flows. Measuring mixing rates between coupled subchannels does not require a visible tracer but involves measuring the amount of tracer effectively introduced in the flow as well as its concentration at the point of interest. Ion solutions for water flows, and chemically active gases for air flows have been largely used and work well, though these measuring systems are rather time consuming and expensive. Measurement of mixing rates through integration of local measurements (Laser Doppler Anemometry or Hot Wire Anemometry) is possible but available technology imposes serious restrictions on geometries and dimensions of the test section (Shen *et al.*,1991). These methods also do not provide subchannel-wise information, that is better suited for subchannel-oriented models, but it has to be calculated by numerical integration.

To be able to use some kind of trace to measure mixing rates and to get flow information we first need an element that introduces a measurable quantity of the trace in the flow in a reduced area, without interfering with the flow. Furthermore the trace so generated has to be measurable with a sensor (or a sensing system) not too intrusive.

Temperature can be used as trace; actually it would be the natural trace to use in thermo-hydraulic studies. In spite of this, the use of thermal traces is not widespread, there have been attempts to use thermal tracers in air flows with very interesting results, but because the temperature of the air is very sensible to any heat exchange, this method is only suitable for local measurements (Guellous and Tavoularis, 1992).

In this work we developed a thermal tracing technique for water flows that compromises an electrical superficial heater, introducing a localized thermal trace, and a temperature sensing system as means to measure the thermal trace “concentration” distribution.

The technique was tested in a simple test section in order to study the technological feasibility. The heat trace “concentration” distribution was measured under

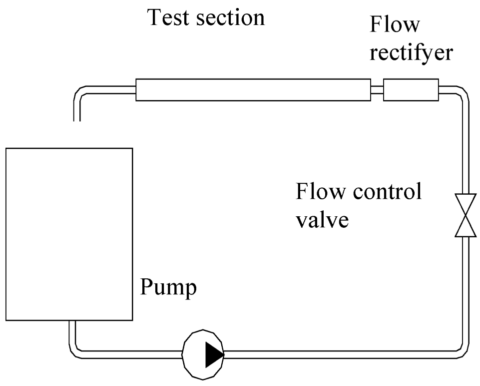


Figure 1: Experimental loop outline.

three different flow distributions, confirming the capability of the method proposed to measure the tracer distribution changes.

II. EXPERIMENTAL SETUP

The experimental method consists in the introduction of a local heat trace in the flow by means of an electrical heater and then measuring the temperature increase downstream respect to the temperature at the inlet of the test section, upstream of the heater. Because the heat rate introduced by the heater is limited, the temperature increase is small as compared to the absolute reference temperature, and a differential temperature measurement was preferred. A platinum resistor option was chosen due to the high sensitivity and linearity achievable and the possibility, with the proper electronic circuitry, of building a differential measuring system.

A. Flow facility

The measurements where carried out on a water loop facility consisting of a water tank, a pump, piping, and the test section. The fluid used was water at atmospheric pressure and room temperature. The water tank had approximately 200*l* volume providing a well mixed and therefore a constant temperature source of water to the pump. Previous to the test section there was a flow conditioner. The layout of the loop is shown in Fig.1.

1) Test Section

The test section consisted on an acrylic pipe with a concentric rod supported at both ends. Part of the rod was replaced with a 100mm long heater of the same diameter. A traversing system was attached to the acrylic tube, allowing the second temperature sensor to be placed in any radial and angular position. The dimensions of the test section are shown in Fig.2.

To have an insight of the measurement possibilities of the method, three measurements were taken in different channel setups. The first configuration was the annular channel with no obstructions. For the second and third measurements two different mixing vanes ("A" and "B" respectively) were clamped to the rod. In both cases the vanes were located 75mm upstream from the second temperature sensor, downstream from the heater.

The first mixing vane "A" was a simple deflector forcing flow in a counterclockwise direction as seen from the heater (looking downstream), as shown in Fig.3 a). The second mixing vane "B" is shown in Fig.3 b). The purpose of this design, with the lower half facing counter clockwise and the upper half in the opposite direction (clockwise), is to create a clockwise vortex motion centered approximately at 13mm of the rod axis. It also has a stronger angle so the mixing effect is expected to be more dramatic.

B. Heater

The heater used in this work is shown in Fig 4. The objective of the heater is to provide heating as localized in the heated surface as possible without disturbing the flow or heating other areas. The heater was a 10mm diameter, 1.5mm thick ceramic tube with a 4μm nickel

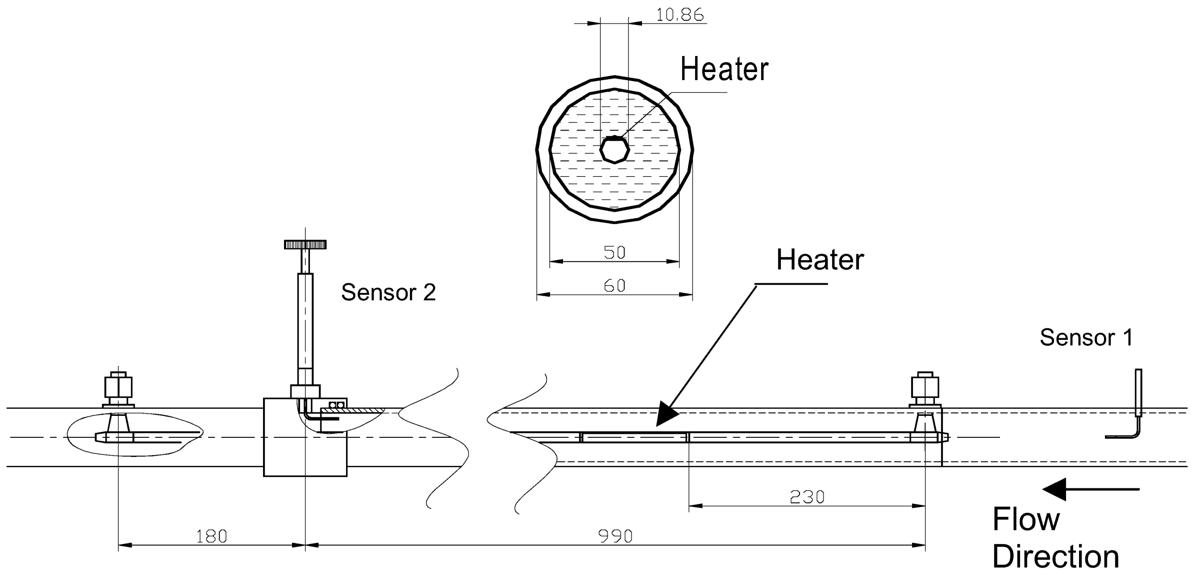
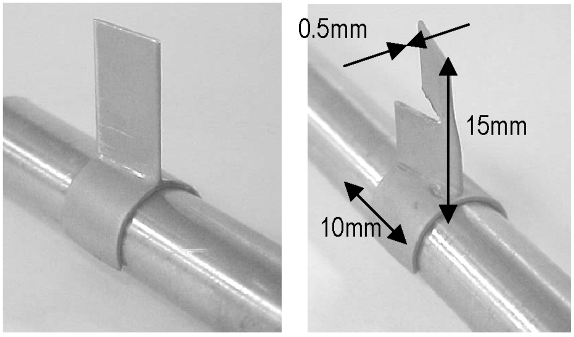


Figure 2: Test section (all dimensions in mm).



(*a*) (*b*)

Figure 3: Mixing vanes. (a) Simple mixing vane (10°) (b) Double mixing vane (20° -20°).

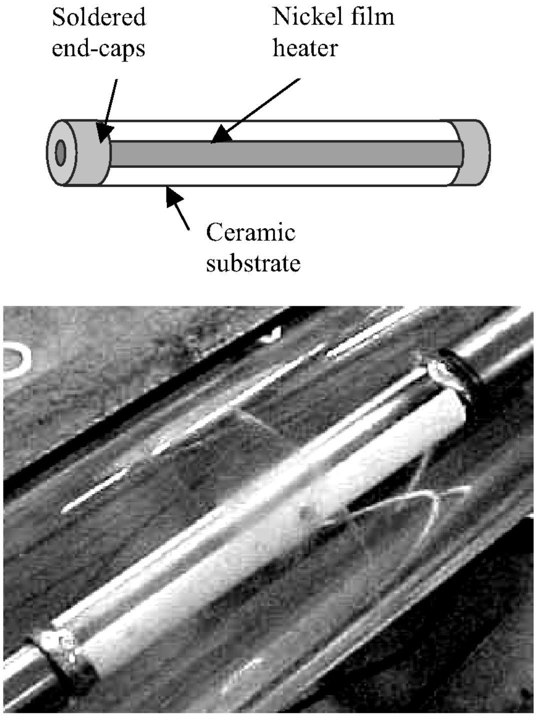


Figure 4: Superficial ceramic-nickel heater.

alloy strap that worked as electrical resistance and covered an angular section of 60°. The nickel film was applied by a chemical and electro-chemical process developed by Dr. José Barbero (Silin *et al.*, 2000).

Two brass end-caps where soldered to the ends of the ceramic tube using a 220°C melting point alloy, providing reliable mechanical and electrical connections. As can be seen in Fig.4 some of the soldering material has been extended over the heating nickel film to avoid the heating of the end-caps.

Due to the use of water instead of air as in previous studies (Guellous and Tavoularis, 1992) the convection coefficient is large and therefore the amount of heat delivered to the fluid by other surfaces than the heater strap is minimized. This heat loss was estimated for a heater temperature of 100°C using a finite element code (with conservative assumptions) and is smaller than 20W. In the present work a heating power of approximately 350W was used and heat losses result in less than 6% of this value, considerably lower than in the air flow case.

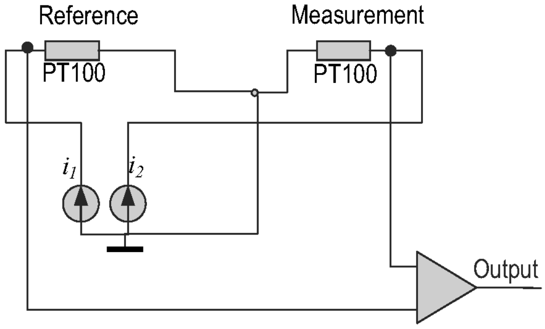


Figure 5: Instrumentation scheme.

C. Instrumentation

As the onset of nucleate boiling on the heater would disturb the flow, if we want to keep the original flow pattern, there is a limit on the power density that can be applied to the heater. On the other hand, the flow considered has large overall heat capacity, resulting in very low values of temperature increase in the flow in the conditions of interest. The bulk temperature increase due to the heater is of order 0.03°C. To measure such small temperature increases two 2mm diameter, 10mm long PT100 platinum resistance sensors were used in a differential measurement mode, allowing a resolution of about 10^{-3}°C. The reference point was a fixed first sensor giving the temperature of the flow at the income. The (relative) measuring point was a second sensor, mounted on a traversing system located 740mm downstream from the beginning of the heater. The PT100 sensors were operated on constant current supplied by a current source circuit similar to the one developed by Peattie (1987). This configuration (Fig.5) is possible due to this highly stable- low thermal drift current source and was preferred to a Whetstone bridge because it provides more flexibility for measurements in multiple subchannels simultaneously in the future. This setup works very well if the sensors involved have the same temperature coefficient and similar resistance values at temperature of interest, the PT100 sensors have very reliable temperature coefficients and are available with very tight tolerance values. The resistance values of the PT100 sensors used in the present work, where equal within 0.1%. In this range currents where adjusted to obtain the same tension to temperature response on both sensors.

A Burr Brown PGA204 programmable gain instrumentation amplifier was used to obtain the difference between the two signal values. The unheated flow temperature was measured from the first sensor.

An orifice plate with a difference pressure sensor was used to measure the flow rate with an estimated accuracy of 5%.

All the signals were acquired with a 12bit analog to digital converter on a PC.

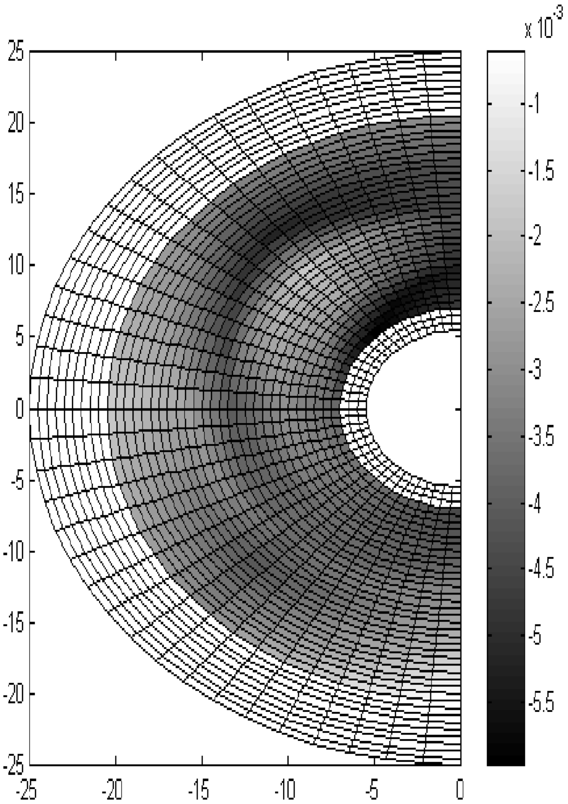


Figure 6: Mean temperature distribution background noise (temperature in °C).

1) Temperature Error Analysis

The goal of the instrumentation used is to measure the mean value of the temperature difference. High frequency components are filtered by the thermal inertia of the PT100 sensor (time constant of about 1sec) and are not analyzed here. The main concern is the slow-varying offset of the measurements. A possible way to evaluate the whole low frequency performance of the method is to perform a complete set of measurements with no heating and measure the background noise as shown in Fig.6.

It can be seen in this figure that the uncertainty is lower than 5×10^{-3}°C.

One of the possible causes of error analyzed here are temperature fronts in the water entering the test section. Temperature fronts in the incoming flow were of mayor concern at the construction of the experimental rig. Different mixers were designed to help the returning water diffuse in the tank water. The temperature signal of the first (test section income) sensor shows the high homogeneity of the incoming flow, with thermal fronts well within 10^{-3}°C.

In Fig.7 there is a time plot of the measured temperature difference when power is supplied to the heater. The sampling rate is 100 samples per second. It can be observed the temperature has slow oscillations. Due to their long period this oscillations cannot be regarded as turbulence but rather seem to be the result of

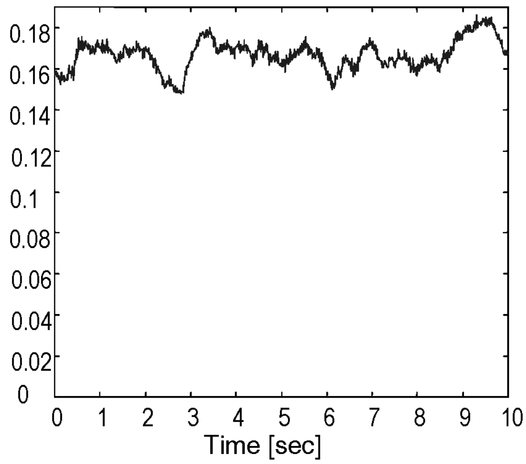


Figure 7: Instant temperature difference values.

Table 1. Test conditions.

	Flow rate [l/s]	Mean bulk Temp. [°C]	$Re\times10^{-4}$	Heating Power [W]
No Vane	2.69	22.5	7.14	357
Vane "A"	2.77	14.4	6.53	337
Vane "B"	2.57	13.7	5.35	350

mechanical vibrations modifying the flow mixing characteristics. These oscillations are averaged satisfactory with the 10 sec sampling time in order to obtain negligible statistic error in the mean value.

III. MEASUREMENTS

As it was mentioned before the measurements were performed on three different arrangements:

1. The test section with no obstructions
2. Test section with mixing vane "A"
3. Test section with mixing vane "B".

The results are shown as adimensional temperature increases calculated as

$$\theta = \frac{\Delta T}{\Delta T_m}, \tag{1}$$

where θ is the non dimensional temperature increase, ΔT is the local mean temperature increase measured between the two sensors and ΔT_m is the calculated increase of bulk temperature due to the heater power,

$$\Delta T_m = \frac{\dot{q}}{\rho\ c_p Q}, \tag{2}$$

where $\dot{q}$ the power applied to the heater, ρ the density, c_p the heat capacity and Q the flow rate.

The Reynolds number was calculated based on the hydraulic diameter as $Re_D = 4Q/P\nu$; here P is the wetted perimeter and ν the cinematic viscosity.

The value of the local mean temperature increase was the mean value of 1000 samples taken at a rate of 100 samples per second making a total sampling time of 10 seconds. This method has a good 50Hz power line noise rejection and also a good rejection over bulk temperature fronts.

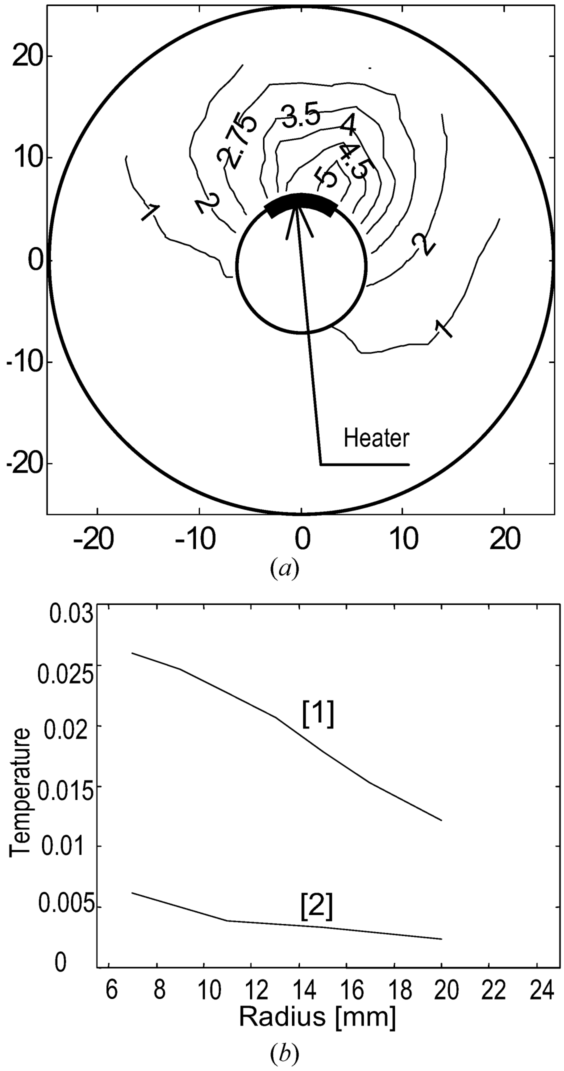


Figure 8: Mean temperature increase θ [ºC]. (*a*) Temperature distribution (no vane); (*b*) Radial temperature profiles at angles [1] 0°, [2] 90°.

The heater operated on constant current of 14 A provided by a direct current power unit. The resistance value of the heater was verified during the runs and it was observed that the resistance value kept within 6% of the initial value.

The values of the test conditions are shown in Table 1.

A. Measurement with no obstruction

The first measurement performed was with no obstruction. Figure 8 shows the temperature mean increase distribution. As it can be observed the hot spot introduced by the heater to the liquid near it was convected with very low diffusion. It can also be observed the capability of the measurement technique to measure this thermal trace and its changes. As the objective of this first work was just to verify the capability of generating a measurable thermal trace, no attempt was done to obtain diffusion parameters from the experiment.

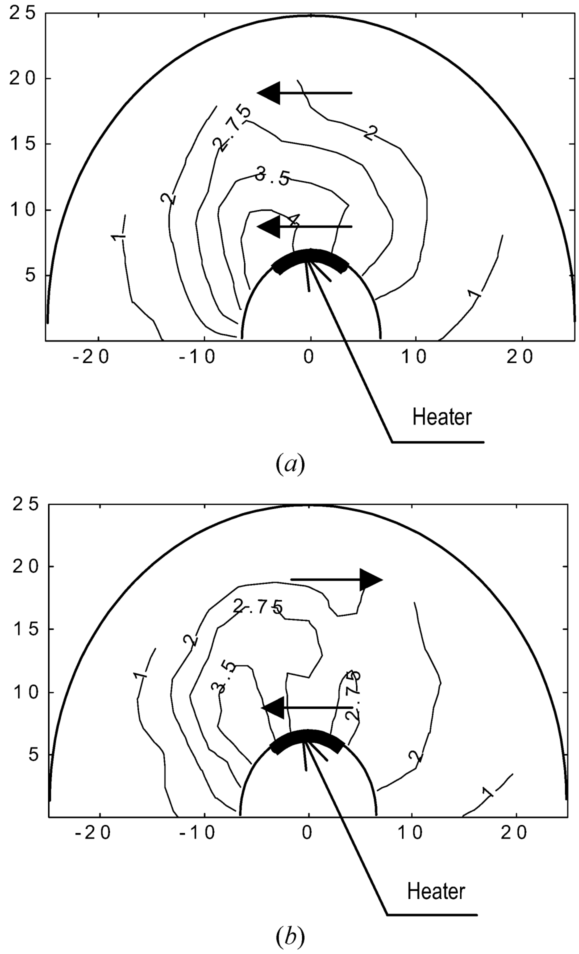


Figure 9: Mean temperature increase θ in flow, test with mixing vanes [°C]. (*a*) Mixing vane “A”; (*b*) Mixing vane “B”.

B. Measurement with mixing vane “A”

The temperature increase field obtained in this case is shown in Fig. 9 (*a*). Clearly the thermal trace has been twisted counter clockwise, showing the effect of the vane, even though the trace stays relatively concentrated. This test shows the ability of the technique to detect movements of the thermal trace.

C. Mixing with mixing vane “B”

Figure 9 (*b*) shows the result of introducing this vane in the flow. The shape of the temperature field resembles a curl, this can be thought as the result of the rotating action of the vortex after the mixing vane “B”. Also this vane design has a more effective mixing action as compared to vane “A”, as can be deduced from the decrease of the maximum temperature value and the spreading of the thermal trace. This test shows the ability of the technique to detect shape changes and diffusion of the thermal trace introduced by an obstruction that affects the flow distribution.

Table 2. Bulk temperature increase, measured and calculated.

	ΔT_m	$\Delta T_m'$
No vane	0.033	0.039
Vane “A”	0.032	0.033
Vane “B”	0.034	0.034
Error	0.006	0.003

D. Bulk temperature

To verify the ability of the technique proposed to measure the total amount of tracer in the area of interest, in this case the whole subchannel, the bulk temperature increase was calculated from the measured values ($\Delta T_m'$) and compared with the one previously calculated by energy balance (ΔT_m). By definition, in an incompressible flow with constant properties, the bulk temperature is (Incropera and De Witt, 1996),

$$\Delta T_m' = \frac{\int_S r\,\overline{u}(r,\theta)\,\overline{T}(r,\theta)\,d\theta dr}{\int_S r\,\overline{u}(r,\theta)\,ds}. \quad (3)$$

Here we approximated the velocity profile with a flat profile $\overline{u}(r,\theta) = u_m$, being u_m the flux mean velocity, and we obtained the following simplified equation.

$$\Delta T_m' \cong \frac{1}{A}\int_S r\,\overline{T}(r,\theta)\,d\theta dr\,, \quad (4)$$

where A is the cross section area of the annular channel. The $\Delta T_m'$ and ΔT_m for each case are shown in Table 2.

The differences between the measured an calculated bulk temperature are within the error margins.

E. Evaluation

The system proposed provides meaningful qualitative and quantitative information. The temperature maps as shown in Fig.8 and Fig.9 provide clear qualitative information about flow direction and mixing efficiency. As have been shown, the background noise is of order 5×10^{-3}°C and does not distort the interpretation of the temperature maps.

IV. CONCLUSIONS

In the present work a new thermal tracing technique has been presented. For the annular channel used to analyze the method feasibility, mean temperature increase has been measured with good agreement with the values calculated by energy conservation. This allows us to be optimistic about the use of this technique to measure turbulent mixing between coupled subchannels.

A map of temperature increases has been obtained, providing information about the mixing in the channel and about the flow downstream two different mixing vanes, showing the possibility of using the thermal tracing system also as a flow visualization technique.

The system was thought as a low-cost facility, is rugged, and does not need sophisticated equipment or calibration. It does not need special laboratory conditions and is able to work with real scale models. The water used was tap water with no special treatment as would be needed for state of the art (Laser Doppler and hot wire anemometry) techniques.

V. ACKNOWLEDGMENTS

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