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**MICRO THERMAL SYSTEMS IN FRANCE :
FROM KNOWLEDGE TO TECHNOLOGICAL DEVELOPMENT**

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Abstract

This paper presents an overview of the research activities performed in France, and presents more precisely the work carried out by the "microthermique" group in Grenoble ("Micro thermal exchanges"), which is composed of 5 teams. Examples of fundamentals and applied research projects on micro-channel heat exchangers and systems are presented.

INTRODUCTION

The growing demand for product miniaturisation in all ranges of industrial sectors leads to new challenges for their thermal management. Furthermore for products such as electronic or power supply components, an efficient thermal control guarantees its reliability.

The objective of the RTD activities performed in France and Europe are to develop micro-heat exchangers for the thermal management of innovative products in order to maximise the compactness and the performances, while minimising materials, working fluids, waste and energy consumption towards the EU's goal of a zero-waste life-cycle for products and manufacturing. Micro-thermal system is the natural evolution of the knowledge and technological development realised in micro electronic and micro-mechanical systems, and micro thermal and fluidic system is an emerging new technology as it is now possible to manufacture ever smaller, more complex elements for cooling of electronic devices, air-conditioning or energy systems such as fuel cells. Significant breakthrough can be achieved in the area of micro-channel heat exchangers based on innovative production technologies developed for the micro-electronic industry, but it requires the combination of

numerous scientific and technical knowledges such as micro-technologies, heat transfer and fluid flow, material and engineering sciences. New skills have to be developed and this requires a global approach including: material developments, design knowledge, development of new production processes and education.

In France, there is strong will to associate the various teams active in these areas, and several initiative and programmes have been launched. These various projects will be described in this paper.

The main industrial applications which can be identified as mature concern heat exchangers for automotive applications (including air-conditioning), thermal management of fuel cells and electronic cooling.

THE FRENCH ACTIVITIES ON MICRO HEAT EXCHANGERS.

The French energy programme

A joint action between the CNRS and the major French research centers (CEA, IFP,...) has been launched and the topic of micro scale heat transfer for various industrial applications. The major issues are micro heat exchangers, micro-reactors for hydrogen production and thermal management of fuel cells and power electronic components.

Within the frame of the Energy program of the CNRS (French Council for Science and Research) an integrated research program (PRI) has been launched in 2002. The aim of these integrated programs is to federate several research teams on a common field and to acquire the basis and the theoretical knowledge for developing innovative energy

technologies. The PRI on micro heat exchangers involves 7 teams and the partners are:

1. CETHIL-INSA in Lyon (Prof. Lallemand)
2. CRTBT in Grenoble (Dr Ayela)
3. IUSTI in Marseille (Dr Tradrist)
4. ISITEM in Nantes (Prof. Perhossaini)
5. LEGI/INPG in Grenoble (Prof. Favre-Marinet, Prof. Bontemps and Prof. Marty)
6. LEMTA in Nancy (Prof. Lebouché)
7. Greth-CEA in Grenoble (Mr. Gruss)

The different aspects of this project are:

- **Hydrodynamic studies in micro channels:**

Single and two-phase flows are studied with the objective to determine friction factors for micro-channels. The effect of the channel geometry, wall roughness and flow conditions are investigated. Local flow measurements will be realised for a better understanding of the major parameters.

- **Boiling in confined space:** Vertical and horizontal natural two-phase boiling flows are also studied. Local flow characteristics such as film thickness will be measured in order to evaluate dry-out phenomena.

- **Convective boiling:** The objective is to identify the boiling mechanisms encountered in micro-channels and to establish transition criteria. Local and instantaneous thermal measurements will be realised for analysing the fluctuations observed in such micro-channels.

- **Sensors and measurements:** This project is essentially experimental, and local measurement is one of the key points for having a good comprehension of the physical mechanism. Micro embedded temperature and pressure sensors will be developed and then used in the various experiments of this project.

Industrial collaboration will be established for both having better information of their need and interest but also to transfer knowledge and develop new applied research project on dedicated technologies. Scientific presentations from members of the integrated projects will be given in this conference.

The network on micro-fluidic

For the micro-fluidic activity a Network has been set-up by the INSA (National Institute for Applied Sciences) in Toulouse. In 2002, 21 teams from university, research centres or industry are participating. The detailed programme can be found on the web-site : <http://www.meca.insa-tlse.fr/microfluidique/index.htm>.

- Objectives

To identify the research teams active in France (basic or applied research and industry)

To exchange information

To identify the industrial needs

To setup technical committees for applied research projects

To organize workshops and conferences

To edit a text book

- Activities

Active control

Capillary Evaporation

Micro flow measurement (liquid and gas)

Micro fluidic components (pump, valve...)

Micro-assembling

Heat transfer at micro-scale

Two-phase flow characteristics

GRENOBLE ACTIVITIES

The technology is progressing at a rate that permanently imposes more sophisticated products as well as a better understanding of the unconventional physics involved in the operation as well as the manufacturing of those minute devices. The primary objective of this section is to review the activity that is developed in the Grenoble Research Centres concerning the cooling of microdevices. The activity of each one of the main Centres which take part to this research will be briefly described.

Activity at LEG (Electrical Engineering Laboratory)

The miniaturization and the development of power components towards high voltage and current ratings lead to increasing power densities. Power components such as IGBTs (Insulated Gate Bipolar Transistor) can dissipate as much as 400 W/cm² but the junction temperature must not overrun 125 °C. Thus, the thermal environment has become a main issue in their performance and reliability (Karim et al. 2001; Gillot et al. 1998, 1999 and 2001).

In many applications, in order to dissipate very high heat flux densities, the required heat sinks have to be larger than the component itself (figure 1). But hot spots appear and the heat flux is not uniform at the heat sink level. Consequently, the heat sink efficiency is poor. This has been the motivation for developing new heat sinks as the one shown in Figure 2 which is made out of silicone exclusively with a silicone oxide layer for the electrical insulation of the component. Small rectangular channels have been designed for cold fluid flow circulation. Figure 3 and 4 show the actual integration of such a device on a chip. Both plasma and chemical techniques are used. Figure 5 shows imperfections of the cutting at the bottom of the slot. Finally, Figure 6 shows the final integration of three of such devices on a three inches wide wafer.

An other powerful technique is also developed in view of spreading the heat and avoiding local accumulation of temperature: this technique is based on the so-called heat pipe technology which consist in using a fluid which evaporates in the hot region and which is condensed in

another region. Different strategies have been considered for the design of the capillary circuits in which the fluid flows from the cold sink to the hot one: both rectangular channels and porous media have been considered (Fig. 7 to 10).

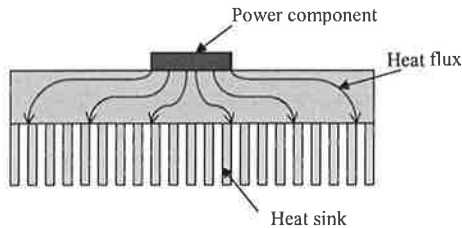


Figure 1: Schematic diagram showing the difference in the scale of the component and of the cooling system.

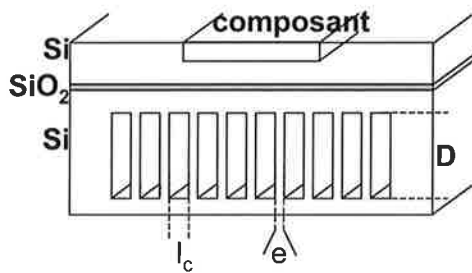


Figure 2: Silicone Microchannel heat sink for high heat flux component cooling (from Gillot 2001).

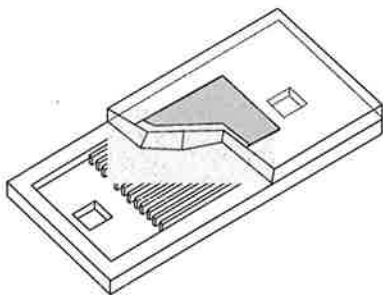


Figure 3: same caption as Fig. 2 showing the rectangular channels in the silicone plate for flow circulation.

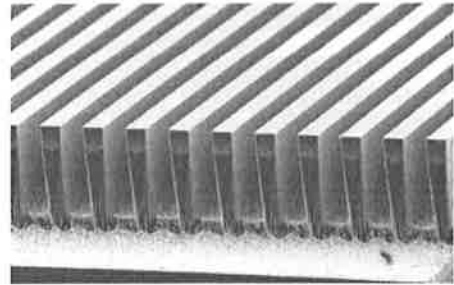


Figure 4: microscopic view of the channels shown in Fig.3. The channel height is 315 μm and the width is 90 μm .

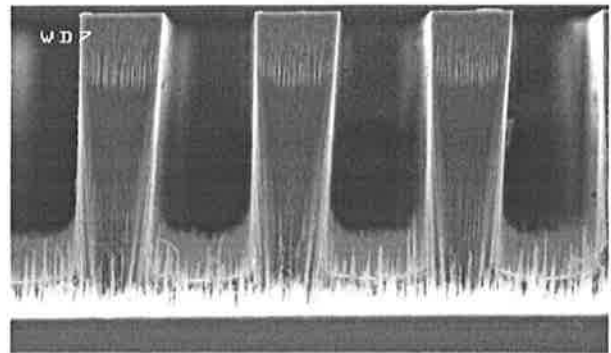


Figure 5: enlargement of the channels at a still greater scale showing surface imperfections at the bottom of the channels.

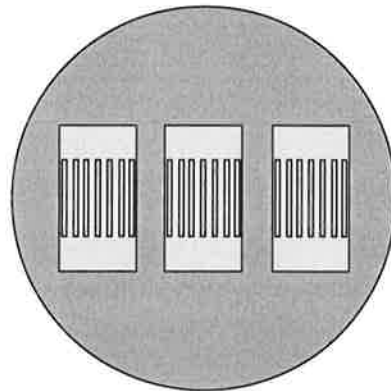


Figure 6: implantation of three heat sinks on a three inches silicone wafer.

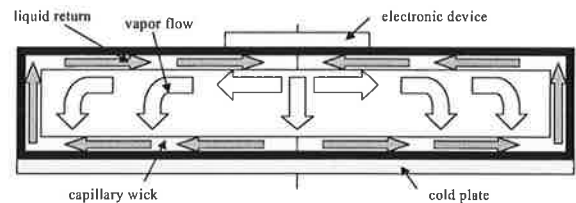


Figure 7: scheme of a heat pipe for electronic cooling.

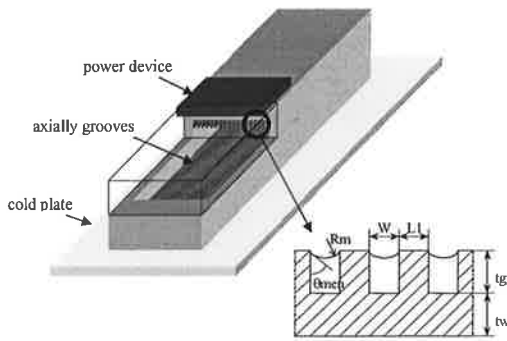


Figure 8 : Heat pipe with axial groove wick.

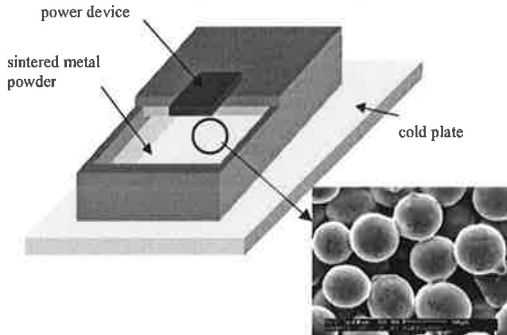


Figure 9 : Heat pipe with metal powder wick.

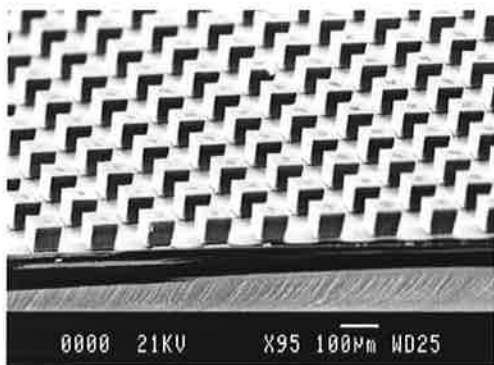


Figure 10 : two dimensional heat spreader made in silicone: typical channel dimension is 100 μm .

Activity at CRTBT (Research Center for Very Low Temperature)

Researches are conducted in the fields of micro fluidics and micro thermal systems for small size technology (Ayela 1999 and 2000 ; Lennon et al. 2001 and 2002). Regarding the micro fluidics activity, microchannels are achieved in silicone and Pyrex. Figure 11 shows a visualization of a two-phase flow entering a silicone microchannel 280 μm wide and 25 μm deep. A Pyrex cover has been sealed onto the silicone substrate allowing an observation with a

microscope. Fig. 12 shows enlarged views of the entrance region. A plane Poiseuille flow boiling is also shown in Fig. 13. Concerning the development of micro-thermal devices, the most spectacular example is shown in Fig. 14: it shows chromium micro tips which have been chemically machined for the sake of local measurement of the thermal conductivity at the nanoscale. Tips height is around 15 μm and its diameter at the top is only 10 nm. These tips are supported by a small heated membrane which temperature is regulated at a constant value. When touching the surface, the thermal leak that is induced by the associated thermal loss is measured and the local thermal conductivity of the surface is deduced. Small size integrated pressure or temperature sensors are also developed.

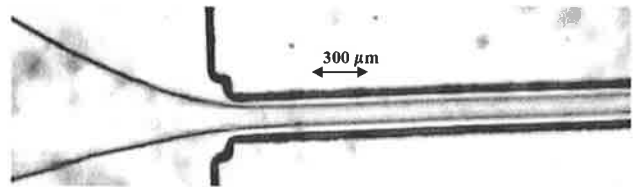


Figure 11: visualization of a two phase flow entering a microchannel 280 μm wide and 25 μm deep

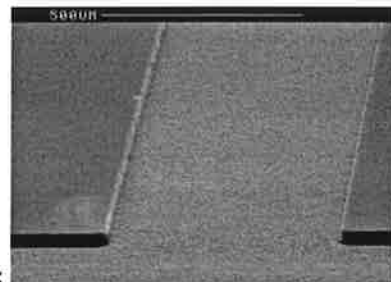


Figure 12: enlarged view of the entrance region of the silicone channel shown in Fig. 11.

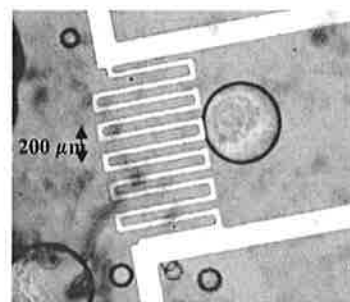


Figure 13: micro boiling with a small size heating element at the channel bottom. The channel depth is 25 μm . Channel width is around 1 mm.

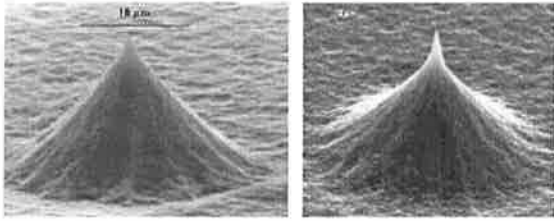


Figure 14: Two different examples of micromachined chromium microtips for local surface temperature measurements: the tip height is around 15 μm and its diameter at the top is less than 10 nm.

Activity at GREth

Two examples of activities which are developed at Greth in the field of microthermal systems will be detailed in this section. The first one concerns minichannel single and two-phase heat transfer, the second the optimisation of compact heat exchangers and the third one the development of new micro exchangers made out of polymers.

Mini-channel heat exchangers. Single and two-phase heat transfer in micro-channels experiments have been conducted on flat extruded multi-channel aluminium tubes (figure 15) (see Agostini et al. 2002 and 2003).

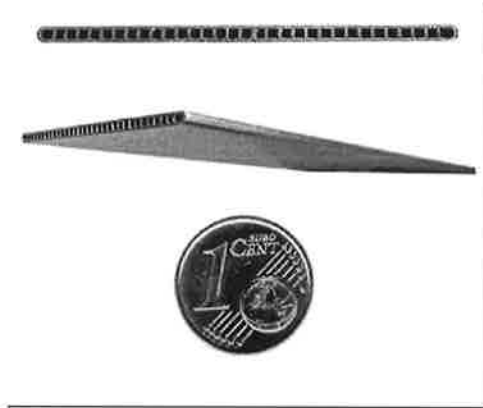


Figure 15: View of the tube tested

The results in single phase flow (figures 16-17) have shown that if the channel geometry is accurately measured, there is major deviation from the conventional theory for larger tube. In turbulent regime, the Gnielinsky and Blasius relations give very satisfactory results. In laminar regime, the friction factor is well predicted by the Shah correlations; but for the Nusselt number it seems that for the smaller tubes, axial conduction has affected the measurements thus leading to 'apparent' very low Nusselt numbers.

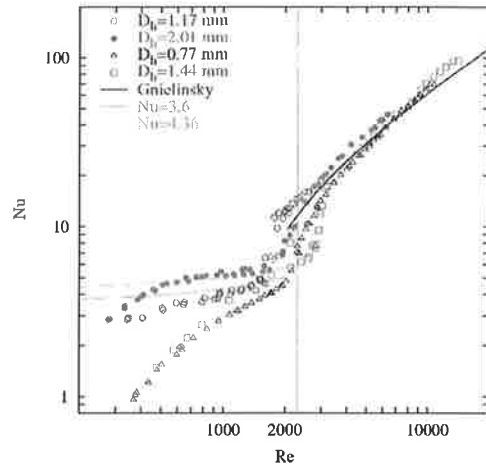


Figure 16: Nusselt number for micro tubes under single phase flow (Agostini ; 2002).

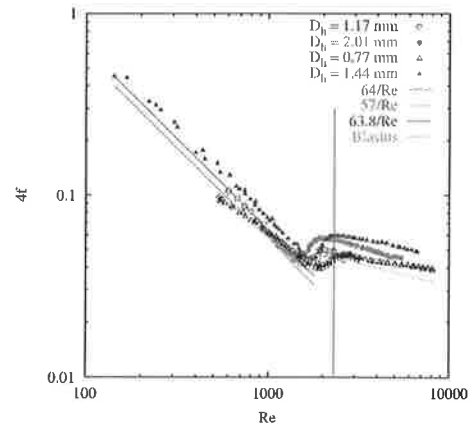


Figure 17: Friction factor for micro-tubes under single-phase flow (Agostini et al. 2002).

For evaporation (figure 18), the results show that there is a significant drop of the heat transfer coefficient, indicating possible dry-out phenomena. Nevertheless the average heat transfer coefficient remains very high. The comparison of these data with conventional boiling correlations fails in most of the case.

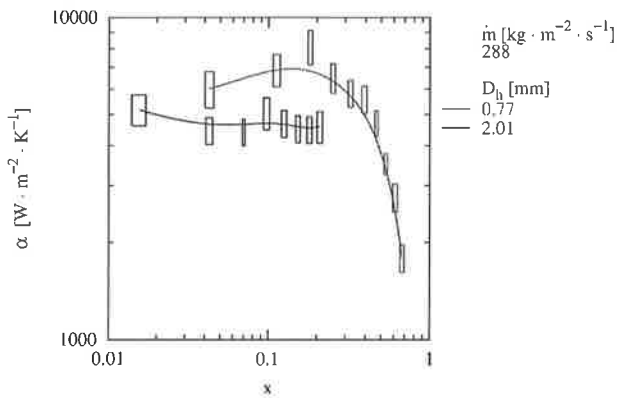


Figure 18: Heat transfer coefficient vs. quality for $D_h = 0.77$ and 2.01 mm.

Compact heat exchanger. With the aim of reducing their size and cost, compact heat exchangers are now able to reach performances as high as $700 \text{ m}^2/\text{m}^3$. Potential applications of such exchangers are numerous: car industry, aeronautics, cryogenics, etc... Their geometry is rather complex as they are designed to enhance the level of turbulence in the flow in order to increase the heat exchanges. Several experimental correlations for compact heat exchangers are available but they still contain too much empiricism to allow the practical design and optimisation of a new product. Numerical simulation is a complementary tool which helps understanding and predicting the behaviour and the performances of such devices. Concerning offset strip fins exchangers (see Fig. 19), Large Eddy Simulation (LES) is used along with more classical models such as Reynolds Averaged Navier Stokes Equations models (RANS) (Michel et al. 2002 and 2003). The unsteady flow over a flat plate is shown in Fig. 20: owing to the small thickness of the walls that are used in such exchangers, the Reynolds number remains moderate. The upstream part of the plate stays laminar whereas it is followed by more delicate regimes which can vary from laminar to turbulent (Fig. 20). As shown in Fig. 21 the prediction of the Nusselt number along the plate is strongly depending upon the numerical model which is used: this emphasizes the necessity to acquire a great expertise before using numerical models. Figures 23 and 23 show a better agreement on the pressure distribution on one hand and on the reattachment length on the other hand.

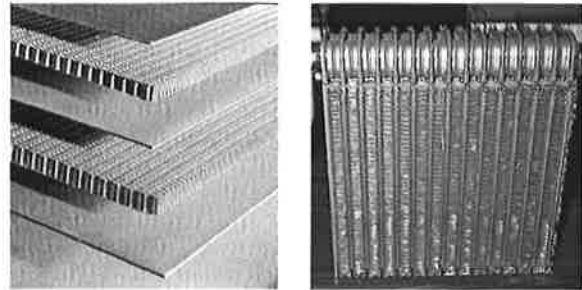


Figure 19: Offset strip fins heat exchangers

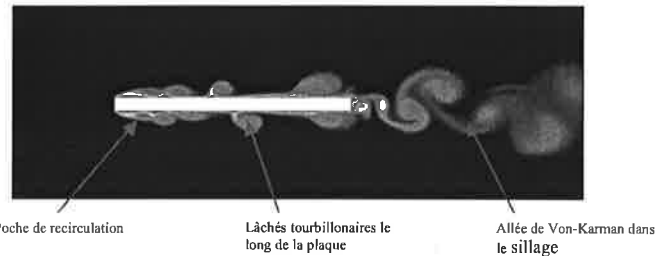


Figure 20: Numerical simulation of the unsteady flow around a plate at $Re = 300$.

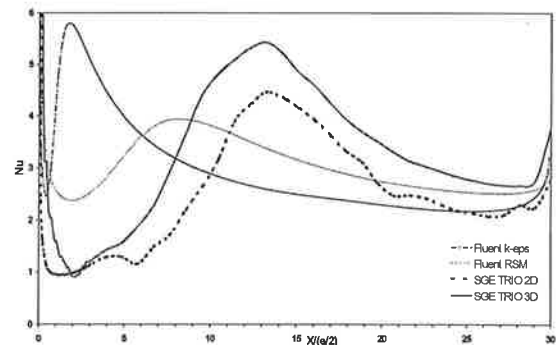


Figure 21 : Axial evolution of the Nusselt number along the plate: influence of the turbulence model

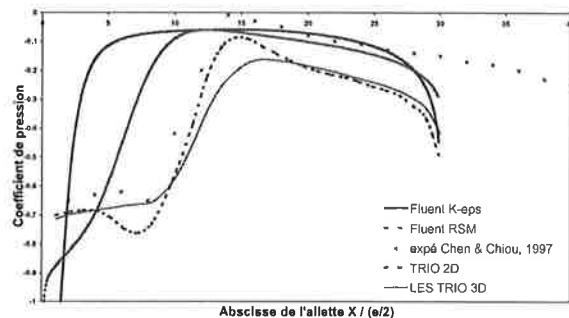


Figure 22: pressure distribution along the plate at $Re = 300$: numerical results compared to experimental data from Chen and Chiou (1997).

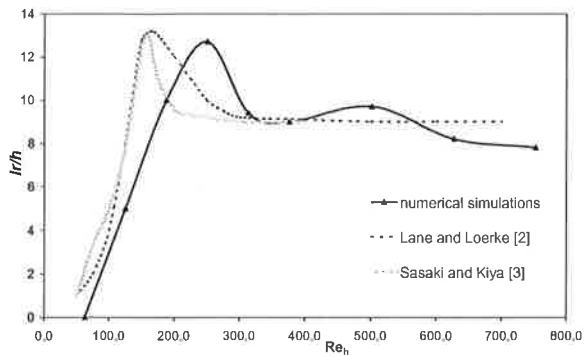


Figure 23: Comparison between numerical and experimental prediction of the reattachment length.

Advanced concepts of micro heat exchangers With the aim of developing new micro exchangers, new materials are being considered such as polymers (see Fig. 24). New measuring technique are developed for this study as a microthermometer made out of gold which is sealed on the plate surface (Fig. 25).

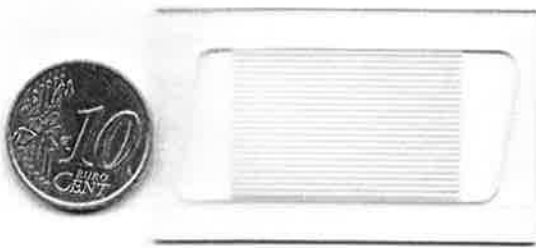


Figure 24: polycarbonate plate for micro exchanger development.

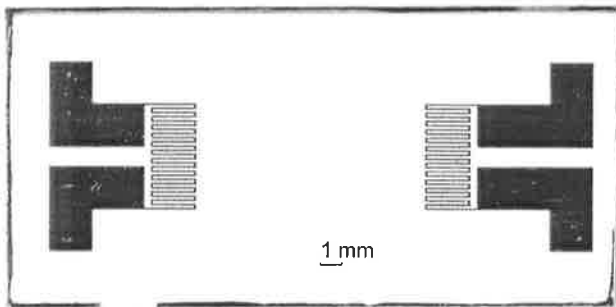


Figure 25 : micro thermometer developed at CRTBT in collaboration with GRETh for temperature measurements in polycarbonate heat exchangers

Activity at LEGI Experimental investigations of the flow and the associated heat transfer are conducted in rectangular and triangular microchannels in order to test possible size effects on the laws of hydrodynamics and heat transfer and to infer optimal conditions of use from the measurements (Gao et al. 2002).

The first experiment is shown in Fig. 26 and consists of a channel with a two-dimensional rectangular section. The spacing between the faces can be varied from 0.1 to 1 mm.

Figure 27 shows the evolution of $C_f Re$ vs. $\frac{L}{D_H} \frac{1}{Re}$. It is

shown that pressure losses are larger than the prediction given in Shah (1978). In the meantime, the heat transfer is lower: they are shown in Fig. 24 which shows the Nusselt

$$\text{number vs. } x^+ = \frac{x}{D_H Re Pr}$$

The second experiment studies the flow in a network of 55 microchannels etched in a silicone wafer and having an hydraulic diameter equal to 110 μm (Fig. 29). Besides experimental investigation, a numerical modelling has been undertaken: the results are reported in Fig. 30.

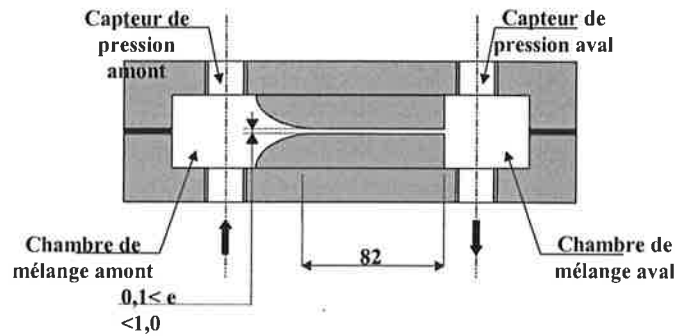


Figure 26 : small size rectangular channel tested at LEGI for pressure and temperature measurements at small Reynolds number.

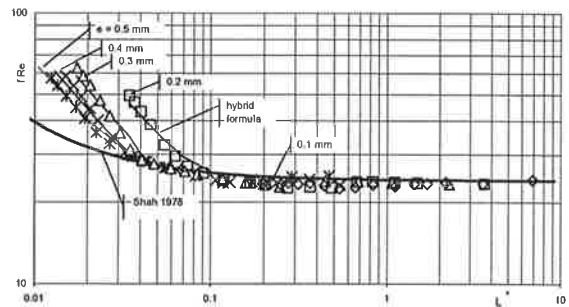


Figure 27: pressure drop measurements vs. channel length.

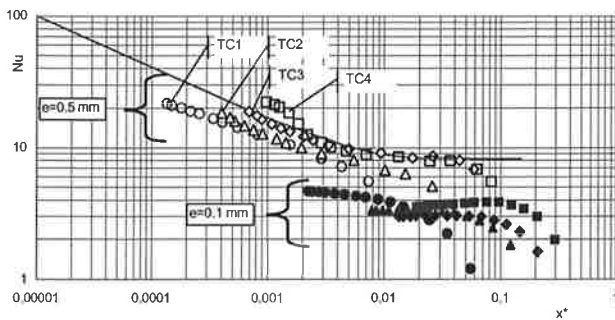


Figure 28: Nusselt number in microchannels vs. the dimensionless abscissa.

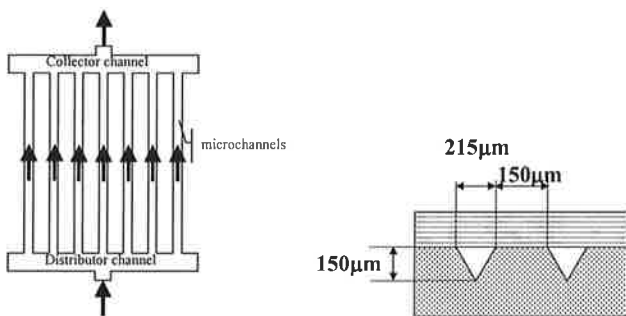


Figure 29: multichannel network with triangular section tested at LEGI.

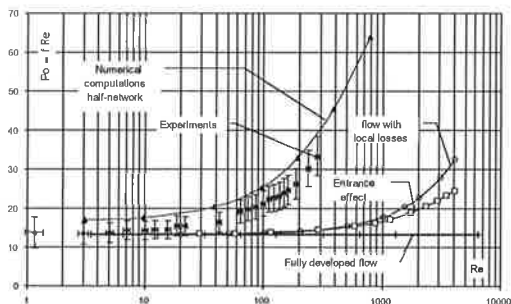


Figure 30: Pressure drop across a network of 55 microchannels etched in a silicone wafer.

CONCLUSION

This paper has reviewed the activity on micro-channel heat transfer and fluid flow in France. There are several teams in research centers, universities and industry that are active, and a significant networking activity between these teams exists.

Work is in progress on micro-instrumentation techniques, and this activity will be developed in the next years, as measurement has been identified as one of the key

points for experimental studies of heat transfer and fluid flow in mini and micro-channels.

Significant progress has been made on the use of compact heat exchanger and micro-channel for single and two-phase (evaporation) applications, and this has led to industrial research projects on refrigeration and air-conditioning.

For electronic cooling, the first applications were for power components. The increasing demand concerning the thermal management of small chips has led to the development of micro-heat pipes that are fully integrated at the design stage of the component. These micro heat pipes are still considered as prototypes, but industrial applications should soon arise.

More generally, our community could take advantage of further efforts in the following directions:

- Development of micro-instrumentation for pressure, temperature and velocity measurements,
- Development of fast measurement for temperature in order to take unsteadiness into account: as an example, the recent utilization of liquid crystal for the study of nucleate boiling seems a promising way for the study of boiling heat transfer in small channels (see Kenning et al. 2001).
- Concerning the development of two-phase flow cooling in micro-channels, the question of the flow distribution in a network of hydraulically connected in parallel

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