PUMPING AND HEAT TRANSFER ENHANCEMENT BY WALL'S MORPHING

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ABSTRACT

In a previous study, heat transfer enhancement using a deformable wall in a heat exchanger was demonstrated numerically using CFD calculations in liquid single-phase situation. This configuration allows the pumping function to be integrated within the heat exchanger itself. Based on these results, a prototype has been developed (but with different dimensions than in the numerical study) in which one of the walls constituting the channel is subjected to dynamic deformations in the form of a traveling wave. Electric heaters on the other wall heat the channel. Actuation is achieved by means of piezoelectric actuators. Experimentally, the pumping function is observed, for all frequencies of deformations and for two different fluids (water and HFE 7000). The heat transfer intensification is also shown, and this in two experimental configurations:

- a pressure difference (which may be zero) between the inlet and outlet of the channel is imposed: in this configuration, the traveling wave imposes the flow-rate. The heat transfer enhancement is then due both to the increase of the flow-rate and the disruption of the thermal boundary layers generated by the wave;
- a flow-rate is imposed with a mechanical pump: in this case actuation has no effect on the pumping, and the measured heat transfer enhancement is then due only to the effects of the imposed dynamic deformations.

First experiments with the presence of boiling were also performed. It was found that boiling can occur even if the fluid does not reach the saturation temperature within the channel. A 100% increase in the mean heat transfer coefficient was found when actuating the channel wall.

NOMENCLATURE

a	[m]	Amplitude of the sine wave
c_p	$[J.kg^{-1}.K^{-1}]$	Specific heat capacity
f	[Hz]	Frequency of the actuators
$\overline{h}$	$[W.m^{-2}.K^{-1}]$	Mean heat transfer coefficient
l	[m]	Channel width
$\dot{m}$	$[\mathrm{kg.s}^{-1}]$	Mass flowrate
S	$[\mathrm{m}^2]$	Surface area of the heated zone
T	[K]	Temperature
$\overline{T}$	[K]	Mean temperature

Special characters

λ	[m]	Wavelength
ρ	$[\mathrm{kg.m}^{-3}]$	Density

Subscripts

in	Inlet
f	Fluid
out	Outlet
w	Wall

INTRODUCTION

Due to the increasing power and miniaturization of electronic components, cooling systems used up to now reach their limits. They can no longer evacuate increasingly important heat fluxes through smaller and smaller areas, while maintaining temperature level low enough to prevent damaging electronic components, or to prevent reducing their reliability. Thus, thermal management constitutes one of the main obstacles to the development of electronics, whether in microelectronics or power. For thermal engineering community, the challenge is to efficiently maintain surface of component at acceptable level (said 120°C) while evacuating heat fluxes above 100 $\mathrm{W.cm}^{-2}$ as short term goal and up to 1000 $\mathrm{W.cm}^{-2}$ for middle term. The technological stakes are very high: it is necessary to develop cooling solutions capable of removing extreme heat fluxes with a limited temperature difference between the hot and cold sources and simultaneously reducing devices scale and increasing systems integration.

Numerous works have been conducted to propose new techniques to enhance heat transfer and to improve existing ones. These techniques are often classified into passive and active one and these latter are detailed in the review from [1]. Among the active techniques, a previous numerical study showed it is possible to reach high heat transfer performances using high amplitude dynamic deformations of a solid within the cooling system [2]. The numerical simulations focused on flow and heat transfer in a sub-millimeter channel whose lower wall is heated and the upper wall is deformed dynamically. All calculations were made in the case of a flow without phase-change (liquid single-phase) with imposed pressure difference between the ends of the channel. Analyses of the results have shown that the dynamic deformation of the upper wall of the channel leads to an important increase in the heat transfer coefficient, whose value is directly correlated to the amplitude and the frequency of the imposed deformation wave.

Simultaneously with the heat transfer enhancement, the traveling wave can be exploited for generating a flow-rate in the channel. Indeed, if the amplitude of the deformation is high enough, a peristaltic pumping can be obtained. It therefore appears possible to realize an interesting multifunctional device using such a deformable system to enhance the heat transfer performance as well as eliminate the requirement of an external pump. The heat exchanger then becomes an "exchanger-pump", which may has advantages in terms of integration. One of the possible deformation means is the use of piezoelectric actuators as indicated by Amokrane [3]. With this type of actuator, it is possible to obtain relatively high flow-rates while maintaining energy cost to a low level.

An exchanger-pump prototype, one of whose walls is dynamically deformed by piezoelectric actuators has therefore been realized to experimentally quantify the flow and heat transfer laws. The experimental device is first described. The experimental results obtained without phase change are then presented. These results were obtained using water as the working fluid. Then, the water was replaced by HFE7000 in order to generate liquid-vapor phase change in the device. The first results obtained in such boiling configuration are described in the second part of the paper.

EXPERIMENTAL SETUP

The prototype is constituted by a deformable rectangular channel of sub-milimetric height whose bottom wall is heated and whose upper confinement wall is deformed dynamically (fig. 1) by a series of piezoelectric actuators to impose a progressive traveling wave. The fluid flows in this space due to the upper wall movement. The bottom wall is equipped with heating cartridge positioned as to obtain an homogenous heat flux on the surface.

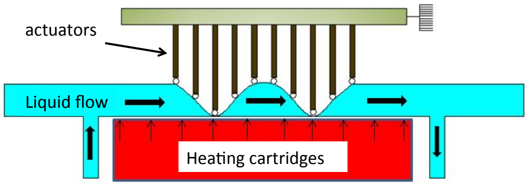

Figure 1. Schematic of the heat exchanger integrating the pumping function

First, the test section is described. The way chosen to generate the deformation wave with piezoelectric actuators is then detailed. Finally, the hydraulic loop is presented, as well as the instrumentation.

Test Section

The test section consists of a rectangular channel 26 cm long, 3 cm wide and about 265 microns thick (see details below). The actuated zone is 16 cm long and 3 cm wide (i.e. 5 cm upward the entrance of the actuated zone and 5 cm downward this zone are not actuated). The bottom of the channel consists in a stainless steel plate in which five grooves were machined to position thermocouples. The heat flux is imposed on the bottom wall of the channel using five heating cartridges High load CCHC Inox Standard (175W, 230V).

The channel is realized by fixing a band of Viton of 1mm thick on the support through a stainless steel strapping. The fluid enters the channel and the flow takes place between the support plate and the band of Viton. This latter is deformed by fluid pressure and inflate thus creating the space where the fluid flow. The Viton choice allows obtaining the convenient membrane deformation with moderate force (i.e. low fluid overpressure).

Piezoelectric actuators are then placed in contact with this membrane to impose a dynamic deformation and to enhance heat transfer.

The channel height is thus dictated by the positions of the actuators. To control this position, the actuators are fixed on a support that can be moved on the three dimensions in order to impose the parallelism, the flatness and the height of the channel.

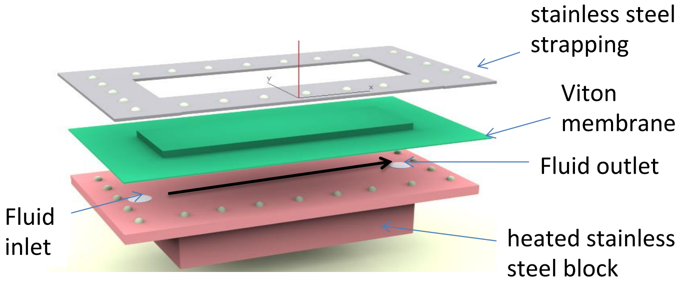

Figure 2. Schematic of the test section: a membrane is fixed on a heated stainless steel block. The working fluid flows between the membrane (Viton) and the heated block thanks to holes realized in the latter at the entrance and at the exit of the channel.

Actuators

There is 10 actuators that are used to generate the traveling wave. Each actuator is composed of two sets of piezoelectric ceramic stack and a deformation amplifying structure (fig. 3). Each stack of ceramic permits deformation of 18 μm. They are disposed on either side of a blade. The latter has a thickness of 1 mm, except in the middle where it is thinner (200 μm). This concentrates the stresses and allows obtaining the maximum deformation at the center of the blade. So, the movement of the ceramics allow buckling the blade of more than ten times the actual elongation of the piezoelectric ceramics.

An aluminum cylinder is fixed in the middle of the blade. It ensures contact between the actuators and the wall to deform.

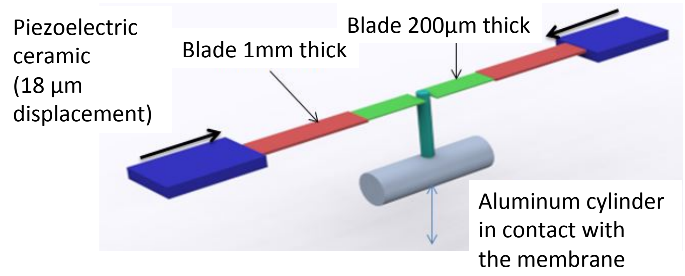

Figure 3. Principle of the displacement amplifying system used for the realization of an actuator

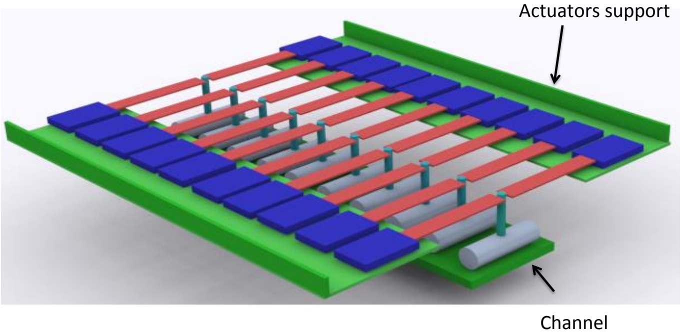

Figure 4. Schematic of complete actuation system consisting of ten piezoelectric actuators with their displacement amplifying system

To generate the dynamic deformation to the Viton membrane, the ten piezoelectric actuators are put into action (Fig. 4). Each vibrate sinusoidally below is maximum (upper) position and their movement are phase shifted in order to obtain a travelling wave. In the following experiments, the wave length was set to 8 cm, the ten actuators allow then obtaining two waves on the length of the heating zone.

Setting of the actuators location

First, each of the actuators has to be adjusted, in order to ensure that the ten aluminum cylinder belong to the same plane, and to ensure that the stainless steel block surface and the actuator planes are parallels and separeted by a known distance.

- Flatness: the position of the actuators support is controlled using three vertical moving plates with micro-metric precision (Fig. 5), for adjusting the parallelism with the heated wall of the channel. A flat strip of wood on which is fixed an aluminum plate of 0.3 mm thick is first inserted between the Viton membrane and the actuators.To adjust the precise position of each of the actuators in the same plane, an electric voltage is imposed between the aluminum cylinder and the aluminum plate. Each actuator is contacted with the aluminum plate using screws binding the actuator to the support. The contact between the aluminum cylinder of the actuator and the thin aluminum plate is obtained when an electric current appears between these two elements.

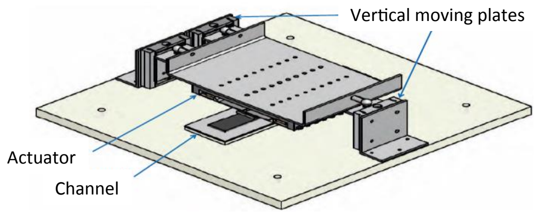

Figure 5. Setting of the actuators: three vertical moving plates allow adjusting the parallelism and the distance between the heated wall and the Viton membrane.

- Distance between the actuators and the heated wall: the position of the actuators support is then adjusted by moving it down step by step thanks to the three vertical moving plates (each of them being controlled by a micro-metric screw). For each vertical position of the actuator support, the actuators are powered-on with an imposed frequency and the resulting flow-rate is measured. Results are shown shown in Fig 6 as a function of the distance between the heated wall and the Viton membrane below an actuator. In these experiments, the pressure difference between the inlet and the outlet of the channel was set to zero (see next section for the details of the hydraulic loop). The distance leading to maximum flow is assumed to correspond to a relative magnitude of deformation equal to 100 % (limit of fully closing the channel when the actuator is in the lower position). This optimum thickness is then imposed in all experiments.

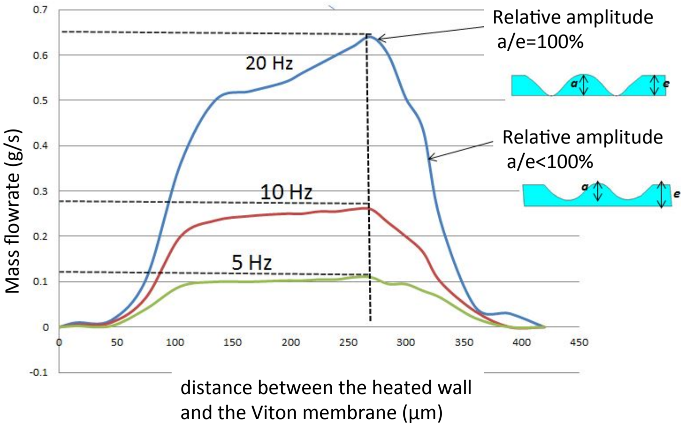

Figure 6. Variation of the measured flow-rate as a function of the distance between the heated wall and the Viton membrane below an actuator, for a pressure difference between the ends of the channel equal to zero.

Hydraulic loop

Figure 7 shows the configuration of the hydraulic system: the pressure at the inlet and the outlet of the channel is imposed by adjusting the vertical position of the two constant level reservoirs. These heights are adjustable and may be changed as required for a given experiment. The pressure difference imposed between the inlet and outlet of the channel during the different experimental campaigns considered in this paper varies between 0 Pa and 400 Pa.

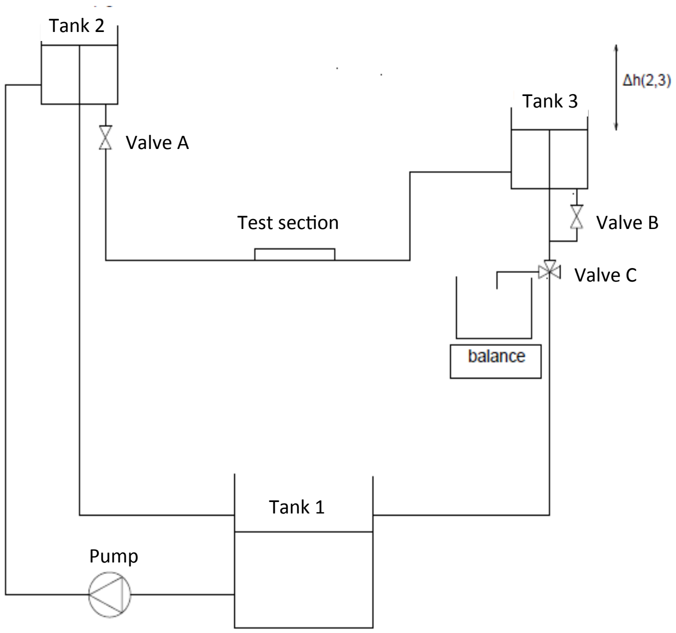

Figure 7. Schematic of the setup: the test section is placed between two constant level reservoirs (tank 2 and tank 3) which vertical position can be adjusted. The tank 1 is the storage reservoir.

The fluid travels the circuit in the following manner:

- The fluid is in the tank 1. It is pumped up in the tank 2 whose level is kept constant by an overflow system that returns the excess liquid in the storage tank 1.
- A flow is obtained in the channel due to the pressure difference between the inlet and the outlet of the system, or by the pumping induced by the dynamic deformation of the Viton membrane when the actuators are powered-on.
- The fluid flows from the outlet of the channel to the tank 3 whose level is also kept constant by an overflow system that returns the excess liquid in the storage tank 1.
- The three-way valve C allows fluid to flow from the reservoir 3 to the balance (to measure the flow rate) or to the tank 1.

The mean pressure of the liquid in the channel is the average hydrostatic pressure imposed by the vertical positions of the reservoirs 2 and 3. This pressure is slightly higher than the atmospheric pressure (which is the pressure in the tanks 2 and 3). All connections are made using with 4 mm in diameter tube, except the overflows from tanks 2 and 3 which have a diameter of 6 mm to prevent chocking.

EXPERIMENTAL RESULTS WITHOUT PHASE-CHANGE

Figure 8 shows the evolution of the mass flow-rate versus the actuators movement frequency. The pressure difference between the channel ends is kept to zero, the flow is generated only by the traveling wave imposed on the Viton membrane. Mass flow-rate first increases linearly for frequencies between 5 and 20 Hz, showing that the device behave like a volumetric pump. Then the slope slightly decreases for frequency between 20 and 40 Hz. It should be noted that the obtained flow-rates are significantly lower than those expected by considering a perfect sinusoidal travelling wave. Indeed, knowing the frequency and the wavelength of the travelling wave, and considering the flow-rate obtained experimentally, one can determine the amplitude a that the wave should have if it is sinusoidal :

$$a = \frac{\dot{m}}{\rho l \lambda f} \tag{1}$$

This calculated amplitude a, for the different frequencies considered in this study, is only 12 μm. This value is significantly lower than the amplitude imposed to the actuators. The waveform is thus not sinusoidal, the deformations of the membrane (swelling) between two actuators being definitely present. The membrane behavior could be divided in two :

- Close to each actuator it follow the expected movement and these 10 zone follow the traveling wave movement
- in the gap between 2 consecutive actuators the membrane swell and damp the movement thus creating inert zone between each moving one.

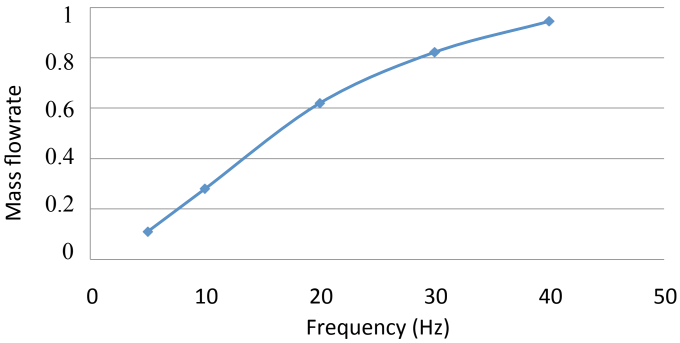

Figure 8. Variation of the measured mass flow-rate as a function of the frequency imposed to the actuators.

A series of experiments was conducted by varying the height difference Δh between the inlet and outlet reservoirs, and the frequency of the actuators. For each Δh, the electric power of the heating elements is adjusted such that the outlet temperature is between 40 and 45°C.

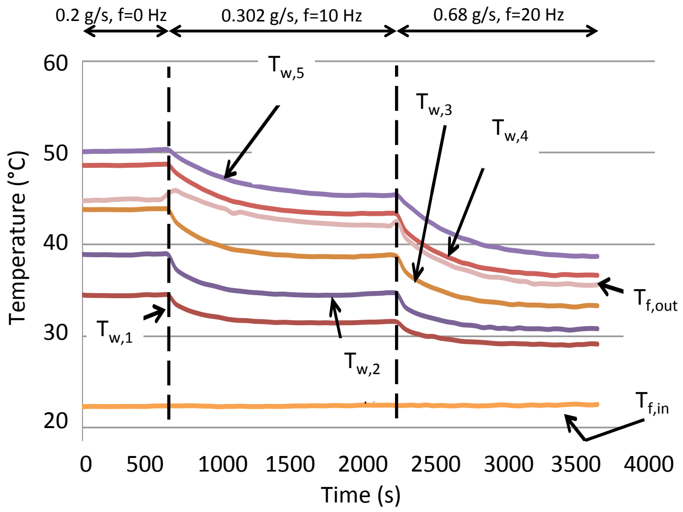

Figure 9. Example of a temporal variation of the various temperatures (wall and fluid) illustrating the effect of the actuators on the heat transfers, for $\Delta p = 200\ Pa$. $T_{w,1}$, $T_{w,2}$, $T_{w,3}$, $T_{w,4}$ and $T_{w,5}$ are the wall temperatures measured at x=0 (abscissa of the actuated zone entrance), 4, 8, 12 and 16 cm (abscissa of the actuated zone end), respectively.

At the beginning of the experiment shown in Figure 9 the actuators are powered-off. When steady state is reached the different temperatures are recorded, and the actuators are turned on at a frequency of 10 Hz. When steady state is reached again, the frequency of the actuators is increased to 20 Hz. As can be seen in figure 9, activation of the actuator causes the sudden fall of the wall and the fluid output temperatures. In the same time the flow-rate increases from 0.2 to 0.302 $g.s^{-1}$, and then to 0.68 $\mathrm{g.s}^{-1}$. This increase in flow-rate explains the lowering of outlet fluid temperature and contribute also to the wall one that is mainly due to the increase in heat transfer coefficient.

The global heat transfer coefficient over the heated surface is determined from the enthalpy balance (eq. 2), and its variations versus the mass flowrate are shown in Figure 10. It can be noticed that using the mean logarithmic temperature difference instead of the difference of the mean temperatures led to the same values of the heat transfer coefficient.

$$\overline{h} = \frac{\dot{m} c_p (T_{out} - T_{in})}{S(\overline{T}_w - \overline{T}_f)} \qquad (2)$$

For a given flow-rate, the heat transfer coefficients is augmented by the actuation as the dynamic deformation of the membrane creates many disturbances in thermal boundary layers. However, this increase remains relatively modest (about 30 % maximum), and below the expected gains according to the numerical analysis of Leal et al. [2]. The modest performance of the experimental set-up are mainly attributed to the degradation of the membrane deformation compared to the perfect sinusoidal travelling wave used in simulation.

To study the effect of the actuation due to the boundary layers disturbance on the heat transfer when the mass flow-rate is imposed (as in conventional thermal management loop), a series of experiments was carried out by imposing the flow circulating in the test section thanks to a volumetric pump. Experiment then consists in imposing a flow-rate by the pump without turning on the actuators. Then the actuators are powered-on at different frequencies, the flow-rate remaining unchanged.
Figure 11 shows that for a constant flow-rate the heat transfer coefficient increases when the frequency increases, which clearly shows that the dynamic and thermal boundary layers are disturbed during the actuation. The increase appears more clearly than when the flow is induced by the actuators alone. It should be noted that during tests at imposed flow, the membrane was significantly more distorted. This indicate that pressure level is higher than in the case of simple actuation. One can thus expect that heat transfer enhancement can be higher for an improved exchanger-pump configuration. Indeed, the chosen membrane is not rigid enough to work efficiently in this configuration and need to be improved for future experiments.

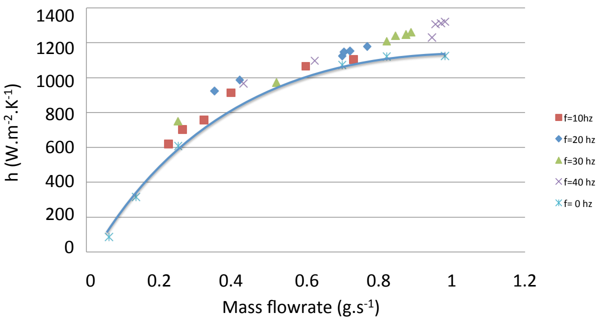

Figure 10. Variation of the heat transfer coefficient (averaged on the heated surface) as a function of the mass flow-rate induced by the actuation. The solid line represents an approximate regression of the results obtained without actuation (f=0 Hz).

FIRST EXPERIMENTAL RESULTS WITH PHASE-CHANGE

Water in the loop was removed and replaced with HFE 7000 which saturation temperature at atmospheric pressure is 35°C and which has a latent heat of vaporization roughly ten time less than that of water. A condenser is added downstream the channel outlet. Tests were first carried out by imposing a pressure difference through the two constant level tanks. The heat flux was then increased until vapor was visualized in the transparent tube immediately downstream the channel outlet.
In this configuration, the formation of vapor generate a two phase flow. This latter lead to very high pressure drop and induce

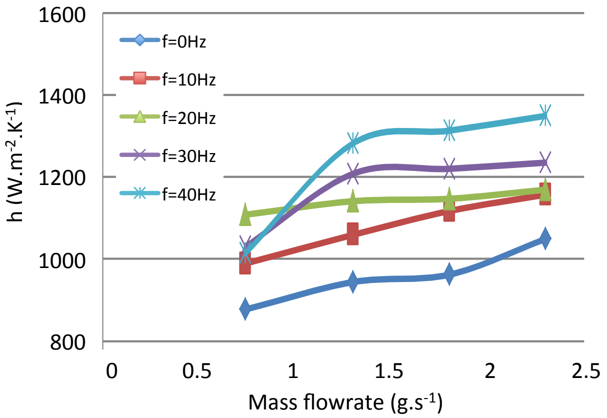

Figure 11. Variation of the heat transfer coefficient (averaged on the heated surface) as a function of the mass flow-rate imposed by a volumetric pump - Influence of the frequency imposed to the actuators

a ”choking effect” that prevents the flow inside the channel. The hydraulic system has therefore been changed, and the flow is forced by a mechanical pumping. It should be noted that this pump was a volumetric one, thus an identical flow-rate in the circuit is obtained when the actuators are active or not. The results of experiments thus provide information on the effect of the actuation of the heat transfer intensification (decoupled from the pumping function).

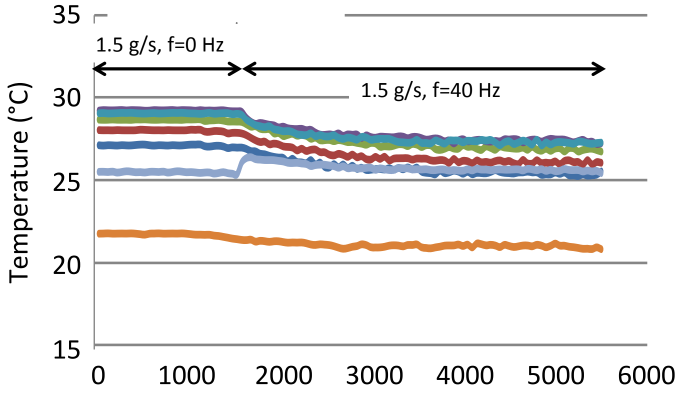

Figure 12. Example of temperature temporal evolutions (of the wall and of the fluid) illustrating the effect of the actuation on the heat transfers when boiling occurs.

An example of result is shown in Figure 12. At the beginning of the experiment, the actuators are not activated. The pump is set at a rate of 1.5 g.s^{-1}. When the steady state is reached, the different temperatures are recorded. Then the actuators are turned on at a frequency of 40 Hz. The activation of actuators causes a decrease of the wall temperatures. The steady state is reached after about 35 minutes.

It may be noted that boiling occurs despite the fact that the temperatures (of fluid and wall) remain constantly below the saturation temperature at atmospheric pressure. The decrease in temperature can be explained by the local pressure repartition. Actuators vertical movement induce important local pressure variations due to fluid acceleration and displacement of the membrane in the vicinity of the wall. During the movement of the actuator vertically downwards, the channel cross-section decreases causing an acceleration of the fluid and therefore a decrease of the pressure. The phase-change then appears at a temperature below the saturation temperature at atmospheric pressure, which is in the sense of an intensification of the heat transfer.

For a mass flow-rate of 1.5 g.s^{-1}, and when the actuators are not turned on, the mean heat transfer coefficient is 330 W.m^{-2}.K^{-1}. At this same flow-rate of 1.5 g.s^{-1} and operating the actuators with a frequency of 40 Hz, the mean heat transfer coefficient is 660 W.m^{-2}.K^{-1}. The heat transfer enhancement is thus 100%.

It should be noted that in these tests, the membrane exhibits large deformations between actuators due to the pressure increase in the channel induced by high pressure drops and liquid-vapor expansion. It is therefore difficult to draw strong conclusions, as the real size and (dynamic) shape of the channel is largely unknown.

CONCLUSIONS

Based on results obtained in a previous numerical study showing that consequent heat transfer enhancement can be obtained using ”wall morphing”, a heat exchanger mock-up comprising one dynamically deformed wall was realized.

Experimentally, the pumping function is observed for all the frequencies imposed to the actuators and heat transfer enhancement has been demonstrated. Global heat transfer coefficients are improved up to 25-30% in single-phase flow and roughly 100% in the boiling case .

The experimental results however reveal weaknesses in this set-up, the main one being that the membrane is not rigid enough and induces unwanted deformations that limit the performance and interpretations. It is however expected that these flow-rates and heat transfer performance can still be improved if the dynamic wall deformation is more similar to the traveling sinusoidal one.

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