EXPERIMENTAL STUDIES OF THE TRANSIENT MIXED CONVECTION IN A VERTICAL PIPE. APPLICATIONS TO THE HEATING RADIATORS.

POPA Catalin Viorel – cv.popa@univ-reims.fr
MAI Ton Hoang – th.mai@univ-reims.fr
POLIDORI Guillaume – guillaume.polidori@univ-reims.fr
Laboratoire de Thermomécanique, UTAP, EA 2061,
Faculté des Sciences, B.P. 1039, 51687 Reims Cedex 2, France.

Abstract. The aim of this work is to observe the flow reversal that can appear at the time of interaction of hot and cold boundary layers in transient mixed convection in a vertical pipe. The instationary character of the flow is due to the application at the entry of the tube of a positive or negative temperature step. The transient mixed convection has a significant contribution in many industrial applications such as the air conditioning systems, the heat exchangers, nuclear plants, etc. The behavior of such apparatuses is well controlled in steady state, which is not yet the case in unsteady state. We designed and built an experimental installation which enables us to visualize the transient behavior of the flow in a vertical tube by laser tomography. The principle consists in creating a laser sheet parallel with the generatrix of the cylinder and observing the flow in this plan. The Plexiglas® tube used to carry out these experiments has a 54 mm internal diameter, a height of 1200 mm and a thickness of 3 mm. The experiments were made for a Grashof number equal to $6.3 \times 10^6$ and for a Reynolds number of 600. When we apply a positive temperature step to the entry of the tube we note that zones of recirculation appear in the vicinity of the wall. This phenomenon is due to the instability of boundary layer.

Keywords: Flow visualisation, Transient mixed convection, Heating, Vertical pipe.

1. INTRODUCTION

The transient mixed convection has a significant contribution in many industrial applications such as the air conditioning systems, the heat exchangers, nuclear plants, etc. The behavior of such apparatuses is well controlled in steady state, which is not yet the case in unsteady state. In real industrial application, a transient laminar flow may occur during normal operation (as in starting processes or when the boundary conditions are normally changing with time) or, most often, due to accidents.

The problem concerning the laminar flow in transient mixed convection in a vertical pipe was studied numerically by many researchers, especially after the appearance of powerful computer in the ‘90s. On the other hand, it is noted that there are not many experimental studies because of significant costs of realization or of encountered difficulties related to the cylindrical circular geometry of the pipe.
The literature usually is interested in the combined effects between free and forced convection through vertical tubes, when a sudden change in the wall temperature or the wall heat flux occurs. The unsteady characteristics of the flow can cause oscillatory and reversed flow phenomena yielding the flow to be unstable. These phenomena have been observed by Martin et al. (1986). This recent interest is related to the problems of safety in nuclear plants which has been studied by Yan (1992) and Lee & Yan (1994). They performed a study to investigate the transient mixed convection in a vertical tube with upward flow and a uniform step of heat flux or temperature applied to the external surface. They were especially interested in the effects of the buoyancy ratio Gr/Re and wall-to-fluid heat capacity ratio on the thermo-hydraulic structure of the flow inside the pipe. Zghal et al. (2001) have shown the significance of the heat conduction effects in the wall on the development of recirculating flow especially for low Reynolds numbers.

However, very few studies are available on the thermo-hydraulic structures in a vertical pipe flow, when the entrance is submitted to variable boundary conditions. Mai et al. (1994, 1999) performed a theoretical study to investigate the transient mixed convection in vertical pipe flows with inlet temperature or volume flow rate steps. The analysis was restricted to the boundary-layer equations rather than the full Navier-Stokes equations, and consequently the stability of the laminar flow was not taken into account.

Hanratty et al. (1958) has made an experimental study concerning a water laminar flow in a vertical tube subjected to a heat flow (positive or negative) on the external surface of the wall. The authors analyzed two cases: that of a heated and a cooled ascending flow. In the first case, they observed that the instabilities may occur when the velocity profile develop points of inflexion. In fact, they have shown that the non-isothermal flow is highly unstable and may undergo its transition from a steady laminar state to an unstable one at a rather low Reynolds number. In the second case, they noticed that the fluid being in the vicinity of the wall is delayed and the velocity gradient at the wall may become zero. Another experimental study was carried out by Bernier & Baliga (1992). They developed a gold-film technique to study upward mixed convection flows of water inside vertical pipes. The experiments were carried out for several cases representative of aided mixed convection flow. Recirculation cells were observed each time in the center of the tube.

Our goal is the design and the construction of an experimental installation making it possible to visualize the transient behaviour of a upward laminar flows of water in mixed convection inside a vertical or tilted tube, when one suddenly disturbs the boundary conditions at the entry of the tube (by sudden application of a temperature step) or at the wall (by quasi-instantaneous heating). The vertical pipe is considered as water heating radiator element.

2. DESIGN AND CONSTRUCTION OF THE EXPERIMENTAL DEVICE

2.1 Experimental set-up

To access the unsteady characteristic of upward laminar flows, we carried out a new experimental installation in our laboratory based on the laser tomography. The experiments were conducted in a Plexiglas® tube which has an internal diameter (D) of 54 mm, 1200 mm of height and 3 mm of thickness, with water as working fluid. The experiments were made for a Grashof number equal to $6.3 \times 10^6$ and for a Reynolds number of 600.

The experimental set-up (Fig. 1) included separately the pipe: two closed, insulated and symmetrical circuits around the pipe, two pumps with variable mechanism with a maximum volume flow rate of 17 l/min, a temperature sensor, two flowmeters type EDM-ST, two thermostated water baths type LAUDA® (E100 and RE120), four electromagnetic sluice gates, an electric circuit allowing to control the electromagnetic sluice gates and a stabilization chamber a length of 70 mm, realized of balls of glass with a diameter of 5 mm.
2.2 Flow visualization experiments

The flow was illuminated by a COHERENT® model laser tuned to 514.5 nm at which its rated power is about 2 W, coupled with a spherically cylindrical optical device to generate a laser sheet parallel with the generatrix of the cylinder. The flow is observed in this plan.

In these experiments, the flow development is sequentially recorded by a digital camera (MINOLTA® DIMAGE 7i) with an exposure time of 1/8 s (eosine) or between 1 s and 2 s (discrete particles) fitted to the unsteady phenomena occurring in such laminar mixed
convection flows. The DiMAGE 7i has a five megapixel CCD sensor and 28 - 200 mm equivalent (7x zoom) lens. The camera was fixed perpendicular to the laser sheet with a distance of 500 mm. We used a manual focus to carry out the photographs. The acquisition is coupled with a computer to make data analysis and manual focus for the digital camera in real time.

2.3 Encountered difficulties

During the realization and the use of the experimental installation, we encountered several difficulties among which we can quote: the presence of water leak and of air bubbles blocked in the body of the electromagnetic sluice gates and the stabilization chamber, the choice of the dye which offers best contrast (eosine, fluorescein), the precision adjustment of the verticality of the tube, reflections of the light generated by the laser sheet at the interior of the pipe, reduction of hydrodynamic entry length of the flow crossing the stabilization chamber, the elimination of air bubbles stuck on the interior wall of the tube when we make circulate a long time fluid at a higher temperature than the ambient temperature.

3. RESULTS

3.1 Checking the assumptions

Being preoccupied with the exactitude of the assumptions that we chose at the beginning, we will start a series of handlings with the aim of checking if we obtain a parabolic velocity profile in the tube for sure and, if such is the case, to determine the vertical X-coordinate to which this type of profile is present. In fact, we want to check if the experimental installation, as we conceived it, does not introduce itself of the disturbances into the tube.

Theoretically, to have a hydro-dynamically developed flow, the hydrodynamic entry length of the flow \((X)\) such as Padet (1990) defined it is:

\[
\frac{X}{D} \approx 0.06 \text{Re}.
\]  

(1)

But, as we have only a limited tube length, we will set a hydrodynamic entry length \((X = 1 \text{ m})\) such as to deduct the maximum Reynolds number that we can use to carry out the experiments

\[
\text{Re} \equiv \frac{X}{0.06D} = 308.64.
\]  

(2)

Therefore, from a theoretical point of view, we should carry out the experiments for Reynolds numbers lower than 309, so that the flow may be hydro-dynamically developed. But, is not enough for us. To avoid this constraint and to increase the maximum Reynolds number that we can use, we added to the beginning of the right length of the tube a stabilization chamber of 70 mm length. Later on, having like purpose to check if the stabilization chamber helps us to have a hydro-dynamically developed flow even for Reynolds numbers higher than 309, we carried out two experiments for two different flow rates: 1.05 l/min (i.e. \(\text{Re} = 438\)) and 1.6 l/min (i.e. \(\text{Re} = 647\)).

Then, we filled only one circuit with water at ambient temperature so as to avoid the heat transfer with outside. We put Rilsan® particles in the water bath, so that we may be able to trace the velocity profiles in a cross-section of the tube. Then, we fixed the volume flow rate of the pump and we let circulate water during half an hour. Afterwards, we started to take photographs on three different levels (257, 697 and 1000 mm) from the tube with an exposure time which varies between 1 and 2 seconds according to the selected flow rate.
Then, we noted that the flow becomes hydro-dynamically-developed beyond a 1000 mm height, whatever the flow chosen between 1 and 2 l/min, i.e. for Reynolds numbers lower than 700. Therefore, in order to check if the velocity profile is parabolic, we treated the photographs and traced the velocity profiles to this height (Fig. 3).

By tracing all the points, we note a lack of data for $0.1 \leq D^+ \leq 0.2$, certainly due to the fact that in this area there is a very intense reflexion of the laser sheet which we could not avoid. Moreover, the difference between the flow measured with the flowmeter and that found after having treated the photographs rises up to 9%. The polynomial regressions, for the two volume flows rate are as follows:

$$V_{Re=438} = -0.044605x^2 + 0.044282x + 0.0028984.$$ (3)

$$V_{Re=647} = -0.061237x^2 + 0.063954x + 0.0048536.$$ (4)

Then, we note that the third coefficient in Eq. (3) and Eq. (4) is not zero. This can be explained of this manner:

- It is an error of measurement,
- we don't succeed distinguishing the tube edges well,
- there is an effect of distortion of the trajectory of each particle due to the curve of the tube.

Among the photographs which we used to trace the velocity profiles for two Reynolds numbers we find those of Fig. 4.
Figure 4 – Photographs of the flow in steady state with Rilsan® particles for various Reynolds numbers: (a) 438 and (b) 647.

We must specify that we used an exposure time 2 s for the first Reynolds numbers and an exposure time 1 s for the second Reynolds numbers.

3.2 Step temperature at the entry of the pipe

To simulate a temperature step at the entry of the tube, we start by filling the two circuits with water at the ambient temperature by the intermediary of the two thermostated water baths. The two pumps are put in operating state, but the circuits remain closed. Afterwards, suddenly, we open simultaneously the electromagnetic sluice gates of the hot circuit and we let circulate the fluid with a significant volume flow rate during a few minutes. Then, simultaneously, we close the electromagnetic sluice gates of the hot circuit and we open the electromagnetic sluice gates of the cold circuit, while letting circulate water with a great flow rate too. This operation, we will reproduce it several times with an aim of eliminating the air bubbles which remain blocked in the body of the electromagnetic sluice gates and the stabilization chamber. Later on, as soon as we eliminated the air bubbles, we close all the electromagnetic sluice gates and we adjust the pumps with the desired volume flow rate in order to begin the experiment.

Afterwards, we fix the temperatures of the two thermostated water baths so that we may have a temperature difference between them. As an example, when we wish to obtain a positive temperature step of 20 °C at the entry of the tube, we fix the temperature of the cold water bath at 20 °C and that of the hot water bath at 40 °C. Afterwards, we make cold water at 20 °C circulate in the cold circuit a certain time, until so that the hydro-dynamically developed flow is reached. Suddenly, we close the cold circuit and we open the hot circuit in which water is to 40 °C. At this time, we start the acquisition of the images with the camera.

In the same way, to impose a negative temperature step on the entry of the tube we makes water pass in the hot circuit during a certain time so that the hydro-dynamically developed flow be established and afterwards, instantaneously, we make the cold fluid circulate at the entry of the tube by opening the cold circuit and closing the hot circuit.
But, to visualize the interaction of the hot fluid and the cold fluid when we wish to apply a positive or negative temperature step to the entry of the tube, we put dye or particles in the hot water bath or the cold water bath.

As an example, we will present an experiment on the laminar transient mixed convection upward flows in a vertical tube, when we apply a positive temperature step to the entry of the tube. In order to carry out the experiments, we used a volume flow rate of 1.4 l/min and a temperature step ($\Delta T$) of +20 °C, i.e. the temperatures of the cold water bath and hot water bath were fixed at 20 °C and to 40 °C. Moreover, the laser power was selected around 0.2 Watts, and the numerical camera was regulated with a focal distance of 4.5", ISO 400 and an exposure time 1/8 s for the dye (eosine) and 1.5 s for the Rilsan® particles. The camera was fixed perpendicular to the light sheet with a distance of 500 mm. However, we were obliged to incline the camera of 10° compared to the horizontal one so as to eliminate certain luminous reflexions at the interior of the tube.

Visualizations by particles of the laminar transient mixed convection upward flows are presented in Fig. 5.

Figure 5 – Photographs of the images of the transient flow with Rilsan® particles for $Re = 556$ and $\Delta T = +20^\circ C$.
Looking at these images, it clearly appears the disordered and complex character of the mixed convection flow. We can see especially the progressive installation of an instability which will be propagated within the principal flow thereafter. For better apprehending these unstable thermo-convective phenomena qualitatively, we present the visualizations obtained by fluorescent continuous tracers (eosine) in Fig. 6. We can see clearly in the first photographs, the arrival of this instability whose contour is of Kelvin-Helmholtz type, resulting in this case from the slipping of the two fluids in contact with different density.

Figure 6 – Photographs of a transient laminar flow catches for positive temperature step at $X = 1$ m for $Ri = 6$. 
This phenomenon can explain why after we applied the disturbance to the entry of the tube the flow accelerates in the center and slows down in the vicinity of the wall. The deceleration in flow can involve an unstable flow structure, which is not turbulent. Moreover, under the buoyancy effect, the flow oscillates with the interface between the boundary layer and the central zone of the tube. Appearance of the recirculation zones in the vicinity of the wall induced by the flow oscillation led to instabilities of the laminar flow characterized by vortex in the Kelvin-Helmholtz type. The flow is hydro-dynamically developed after one minute. This observation is compatible with the experimental study carried out by Baudoin et al. (1991) on a heating radiator when the entry is disturbed by a variation in the fluid temperature.

When we apply a negative temperature step to the pipe entry (Fig. 7), the fluid slows down in the center and, at the same time, to keep the mass conservation of the fluid, it accelerates in the vicinity of the wall. In this case, the flow reversals occur in the central region because in this area the fluid slows down so that we have an inflection in the velocity profile.

Figure 7 – Photographs of a transient laminar flow catches for negative temperature step at $X = 1 \text{ m}$ for $Ri = 6$.

4. CONCLUSION

This paper presents the new experimental installation in course of development in our laboratory, while having like purpose to visualize the transient upward laminar flow in mixed convection in a vertical pipe.

Looking these handlings, it clearly appears the disordered and complex character of the laminar mixed convection upward flows. When we apply a positive temperature step to the entry of the tube the instability whose contour is of Kelvin-Helmholtz type, appear from the slipping of the two fluids in contact with different density.

The study of the recirculation zones of the Kelvin-Helmholtz type, allows to better understand the mechanisms of the heat transfer in mixed convection, in a water heating radiator.

The experimental installation is perfectible and the improvements envisaged should enable us to apprehend the problem under a more quantitative aspect, starting from obtaining reliable dynamic fields of the flow and deduced physical sizes (pressure, velocity, etc...).
REFERENCES


