Thermoconvective instabilities in an open flow

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ABSTRACT. The aim of the present study is an experimental investigation of thermoconvective instabilities in a mixed convection phenomenon. The flow of fluid (water) in a horizontal rectangular duct uniformly heated from below is considered. According to the fluid velocity and heat flux supplied to the wall, several flow regimes occur. For moderate Reynolds numbers (300<Re<1200) a thermoconvective instability appears. It manifests itself through sporadic fluctuations of the fluid temperature. Amplitude of fluctuations and laminar durations are time varying. This paper concerns the description of this phenomenon and the characterisation of this intermittency.

1. Introduction
This paper deals with thermal instabilities occurring in a mixed convection phenomenon. It concerns an incompressible flow in a horizontal rectangular duct heated from below. Heat flux supplied to the fluid induces a secondary flow, which is superimposed on the main forced flow.

The mixed convection flow in horizontal ducts has been widely studied [1, 2, 3, 4, 5, 6]. During the first half of the twentieth century, research on this subject attempted to explain certain meteorological phenomena. More recently applications have been concerned with technological processes such as the cooling of electronic components or the production of thin films in CVD reactors; these works have mainly focused on the heat transfer enhancement related to thermoconvective structures in the flow. Results of the linear hydrodynamic stability theory have shown that the thermally stratified Poiseuille flow remains stable as long as the Rayleigh number Ra does not exceed a certain critical value, i.e. Ra*=1708. Beyond this value, the basic flow becomes unstable and two kinds of thermoconvective structures, called “transversal rolls” and “longitudinal rolls”, may appear. Such results concern the case of constant temperatures imposed at the upper and lower horizontal faces of the channel; of course the upper part is colder than the lower one. The aim of our study is to investigate thermoconvective instabilities in the case of an imposed heat flux at the lower horizontal wall.

2. Experimental set-up
Our experiments concern the study of the flow of a fluid (water) in a horizontal rectangular duct uniformly heated from below. The channel is in Plexiglas 3 mm thick. Dimensions are 1.4 cm in height, 2.6 cm in width and the total length 2 m. The 0.5 m central zone that is not insulated from the environment corresponds to the testing zone. The first part of the channel (before the testing zone) enables the fluid to be established hydraulically so that the flow is Poiseuille type at the inlet of this zone. The testing zone wall that is in copper is heated electrically by applying a direct electric current between the input and output terminals. The heat flux is uniform on the straight section throughout the testing zone and can vary from 76 W.m⁻² to 30 kW.m⁻². The exploited information is fluid temperature...
measured by thermocouples and fluid velocity field using the PIV. Many experiments were made for various flow rates and heat fluxes supplied to the wall. For a given fluid velocity and heat flux, we measure fluid temperature in various locations by means of a type K thermocouples, which can sweep the height of the duct.

3. Results
For a given fluid velocity $v$ and heat flux $P$, we measure fluid temperature in various locations by means of a type K thermocouples, which can sweep the height of the duct. Experimental measurements show that the fluid temperature is higher at the top than in the center of the cross section. This shows that the mixed convection phenomenon is installed. In fact, the fluid heated in the lower part of the section, being lighter, goes towards the upper part of the cross-section. At the top, the colder fluid, therefore heavier, goes down by gravity towards the lower part. Thus, we have formation of the convective rolls.

Several series of measurements were carried out in order to cover a large range of fluid velocities. The results obtained allow highlighting various regimes and in particular a domain of thermoconvective instabilities; a classification of signals has been established elsewhere [7]. For low Reynolds numbers, signals are constant versus time. However, it is interesting to notice that even in this regime, the flow structure is complex. For a given range of fluid velocities and heat fluxes supplied to the wall, these signals become instable. In the following, we will characterize the temporal evolution of the fluid temperature signals obtained.

The instability phenomenon manifests itself through large amplitude fluctuations of the temperature signal. The occurrence of these fluctuations is sporadic and the duration of the laminar phases are time varying. In order to illustrate, figure 1 displays such signal.

Classical analysis like Fourier Transform are not well adapted. Indeed, the obtained spectrum highlights a $1/f$ behaviour. In order to define this evolution, a signal analysis procedure was used. Temperature signatures are confined within a temperature interval defined by upper ($T_{sup}$) and lower ($T_{inf}$) boundaries. The procedure consisted in assessing the number $n$ of time intervals for which $T>T_s$, with $T_s$ a temperature threshold which is made to vary with a $\Delta T_s$ step [8]. It is obvious that for a given $T_s$, the durations of the laminar phases are time varying, however, in this case we will be interested by their number and not by their temporal distribution. The corresponding histogram will be called “cutting”.

![Figure 1: Fluid temperature evolution (Re=300)](image)
The statistical distribution of the durations of the laminar phases is a magnitude which is usually considered in the case of intermittency phenomena. Intermittency study shows that there are four kinds of intermittency: type I, II, III [9] and on-off [10]. These types of intermittency are associated to the distribution of the durations of the laminar phases.

These types of intermittency manifest a power law concerning the distribution of the durations of the laminar phases, i.e., \( P(t) \propto t^{-\alpha} \). However, they are not incompatible with a mixed law such as \( P(t) \propto t^{-\alpha} e^{-\gamma t} \). In this case, the power law behaviour could be achieved only when \( \gamma \) goes to zero; otherwise we get an exponential decay of the distribution. When we consider experimental signals, it is not very easy to estimate exactly the threshold for which \( \gamma \) goes to zero.

In order to determine the distribution of the durations of the laminar phases of the experimental temperature signals, we compute the durations of the laminar phases for which the temperature remains smaller than a threshold temperature \( T_s \). \( T_s \) can vary from one experiment to an other, depending on fluid velocity or heat flux supplied to the wall, for the distribution the considered \( T_s \) corresonds to the maximum of the “cutting” histogram. The total duration of experimental signals is about seven hours.

For a wide range of Reynolds number (Re varying from 300 to 1000), an intermittent signal occurs. We can notice that for the various heat flux where this signal is intermittent, the same behaviour is observed (see figure 2), the only differences concern the value of the steady state, the amplitude and the frequency of the fluctuations.

![Figure 2](image)

Figure 2: Histograms corresponding to the “Cutting” curves of intermittent signals for various Rayleigh numbers (Re=800)

Analysis of various signals, for a wider range of Reynolds (Re) and Rayleigh (Ra) numbers, show an exponential decay of the distribution. However the \( \gamma \) coefficients vary when the control parameters vary. Figure 3 gathers the \( \gamma \) coefficients in a [Re-Ra] plane. We can distinguish on the diagram three zones according to the magnitude of \( \gamma \) coefficients. For Re<1000, and low Ra, \( \gamma \) coefficients are small, for Re>1200 or moderate Ra, \( \gamma \) coefficients are medium and for Re>1800 or high Ra the \( \gamma \) coefficients are large. This diagram is in good agreement with the signal classification established elsewhere [7]. The turbulent signals are associated to the large values of \( \gamma \) while the intermittent signals correspond to the small ones.
Then for a given Reynolds number, we carry out the $\gamma$ evolution versus Rayleigh number in order to estimate the critical Rayleigh number for which $\gamma$ tends to zero (see figure 4). Indeed, in this case, the system will tend to a power law distribution. This evolution is not very accurate and does not allow to estimate precisely the critical value of Rayleigh for which $\gamma$ tends to zero. For Rayleigh numbers in the neighborhood of the critical Rayleigh, statistic is not sufficient enough, fluctuations of considered signals become more and more rare. So, the obtained $\gamma$ coefficient is not sufficiently correct and we can not extrapolate its behavior neighboring the threshold.

The range of Rayleigh corresponding to the critical Rayleigh for which $\gamma$ tends to zero is rather large, so two remarks could be made:

- if the critical Rayleigh number corresponds to the frontier for which experimental signals are stable, in this case the power law does not exist. The frontier corresponds to non fluctuating signals which leads to that $\alpha$ et $\gamma$ are equal to zero,
- in the opposite case, the power law exists; \( \alpha \) is different from zero when \( \gamma \) tends to zero. In order to estimate correctly its value, we have to increase the length of the recorded signal. Experimentally it is difficult to maintain the same experimental conditions for a long time.

4. Conclusion

This paper concerned thermal instabilities in a mixed convection phenomenon. Within a certain range of Reynolds and Rayleigh numbers, temperature signals have an intermittent shape. A study of the distribution of the laminar phases durations was carried out in order to define the behaviour of this distribution. We first suppose that this distribution follows a mixed law including a power law and an exponential decay then we look for the critical Rayleigh number so that the distribution tends to a power law. In this case experimental signals have to be very long (large time acquisition) in order to provide a good statistic. This fact is rather difficult since it is not very easy to maintain constant the experimental conditions for a long time.

5. References

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