BOUNDARY LAYER ATTENUATION IN TURBULENT SODIUM FLOWS

DENIS TENCHINE
Commissariat à l'Energie Atomique
Centre d'Etudes Nucléaires de Grenoble
17, rue des Martyrs 38054 Grenoble Cédex 9 - FRANCE
Fax : (33) 76.88.50.45

1. INTRODUCTION

Temperature fluctuations are produced in the sodium coolant of Liquid Metal Reactors when flows at different temperatures are mixing. That occurs in various areas of the reactor plant, in the primary and the secondary circuits. This paper deals with secondary circuit pipings, specifically the Superphenix steam generator outlet. The possibility of thermal striping in this area is studied because of the mixing of a main "hot" flow surrounded by a smaller "cold" flow in the vertical pipe located below the steam generator.

This work was developed in the frame of a collaboration between CEA, EDF and FRAMATOME.

The purpose of our study is to measure temperature fluctuations in the fluid and on the structures, on a sodium reduced scale model of the outlet region of the steam generator. We want to evidence the boundary layer attenuation by comparing wall and fluid measurements. From these experimental data, we shall propose a methodology to predict the boundary layer attenuation and the temperature fluctuations at the surface of the structure, for pipe flow configurations.

This paper is based on the work presented in detail by J.C. BUFFET [1]. The effect of boundary layer attenuation has also been shown by N. SHERIFF and al [2] in a configuration of subassembly outlet flow.

2. EXPERIMENTAL CONDITIONS

The experimental device is a 1/5 scale model of the Superphenix steam generator outlet area (fig. 1). The main "hot" fluid flows downwards along a vertical tube of 0.2 m in diameter. The secondary "cold" fluid is discharged through 12 holes at the periphery of the main flow.

The mixing area is then located along the vertical pipe wall. This pipe has a conical first part of 154 mm in length, connected to a cylindrical part.

The main flow can vary from 20 m^3/h to 180 m^3/h and the secondary flow can vary from 2 m^3/h to 20 m^3/h. The temperature difference can reach 150°C.

The characteristics of the tests are summarized in Table 1. Various test conditions have been performed :

. Reynolds number from 10^5 to 10^6
. mean velocity from 0.2 m/s to 1.5 m/s
. velocity ratio between hot and cold flows from 1 to 3
. temperature difference from 20°C to 150°C

Temperature measurements are made with thermocouples of 0.25 mm and 0.5 mm in diameter. These thermocouples are placed on transversal rods at 10 mm, 82 mm, 154 mm, 205 mm, 315 mm, 425 mm, 535 mm, 645 mm and 755 mm from the level 0 (fig. 1). The rods are located at various azimuthal angles to prevent any wake effect on the downstream measurements. Each rod supports thermocouples placed at 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 10 mm,... from the wall. A thermocouple is installed in a groove at the wall, in front of each set of measurements.

The measurement of temperature fluctuations is obtained through :

. a precise isothermal reference (± 0.1°C)
. a high-pass filter at 0.02 Hz (12 dB/oct)
. a rejection of 50 Hz noise

3. TEST RESULTS

We present radial profiles of mean temperature at axial positions $\frac{x}{D} = 0.4$, $\frac{x}{D} = 0.75$, $\frac{x}{D} = 3.7$, for the test 1 (fig. 2). These profiles show the evolution of the mixing layer between the main hot flow and the surrounding cold flow.

Then, we present the rms of the temperature fluctuations as a function of the distance from the wall, for the test 1 (fig. 3). At $\frac{x}{D} = 0.4$, the temperature fluctuations show two maxima located at $\frac{y}{D} = 0.03$ and $\frac{y}{D} = 0.14$. The first maximum seems to be a consequence of the jets discharged through the holes; the second and main maximum corresponds to the mixing between the main hot flow and the cold flow. As the distance from the origin increases ($\frac{x}{D} = 0.75$ and $\frac{x}{D} = 3.7$), the maximum of temperature fluctuations decreases and the area concerned by fluctuations expands.

Power spectra density (PSD) of temperature fluctuations are presented for measurements at $\frac{x}{D} = 0.75$ and at $y = 0, 2, 3, 4, 5$ mm from the wall (fig. 4). We can note that the energy of the signal is decreasing more quickly with frequency at $y = 2$ mm than for the larger distances. This effect is more evident at the wall where the energy of the fluctuations is clearly lower than in the fluid, especially at frequencies higher than 1 Hz. So, high frequency fluctuations corresponding to small eddies are appreciably attenuated by the thermal diffusion of sodium in the boundary layer.

We present the ratio of fluctuation amplitude at the wall on fluctuation amplitude in the fluid as a function of frequency, at $y = 2$ mm (fig. 5), $y = 5$ mm (fig. 6), $y = 10$ mm (fig. 7). The attenuation effect increases with frequency as previously shown on PSD. The attenuation is also increasing with decreasing Reynolds number, due to the more important influence of thermal diffusivity.

4. PREDICTION OF BOUNDARY LAYER ATTENUATION

The boundary layer attenuation on temperature fluctuations is shown on previous experimental data. A first approach to evaluate the BLA effect has been proposed by LAWN [3]. It consists of a 1D conduction calculation coupling a layer of static sodium (conductive sublayer) and the wall. The calculation results are compared with experimental data (fig. 5, 6 and 7). The conductive model over-estimates the attenuation effect; so, it should give non-conservatism predictions of the temperature fluctuations at the wall and it is necessary to define a more realistic approach.

As the previous method does not take into account the non negligeable influence of the turbulent thermal diffusivity, we propose to find an "effective" thermal diffusivity α' and to introduce it in the previous modelisation. We performed such calculations for the various frequencies, the various distances to the wall and the various Reynolds numbers. For each test condition and each distance to the wall, we find the "effective" thermal diffusivity which fits the best with experimental data for the whole range of frequencies (fig. 5, 6, 7).

Then, we have plotted the dimensionless effective thermal diffusivities $\frac{\alpha'-\alpha}{\alpha}$ against the local Peclet number based on the friction velocity and the distance to the wall (fig. 8). We note the quasi-linear evolution of the curve in the range $0 < Pe^* < 15$. We also plotted other sodium experimental data : a pipe flow with uniform heat flux at the wall by BUNSCHI [4] and a flow at the outlet of a mixing device [1]. These experimental results confirm the correlation between $\frac{\alpha'-\alpha}{\alpha}$ and Pe*.

So, we propose this correlation $\frac{\alpha'-\alpha}{\alpha} = 0.5\, Pe^*$ to estimate the "effective" thermal diffusivity α' in the conductive sublayer of a sodium boundary layer.

5. CONCLUSION

The boundary layer attenuation is shown to be a significant effect in turbulent mixing pipe flows. The sodium results obtained on our model display the role of sodium thermal diffusivity in the conductive sublayer. The amplitude of temperature fluctuations decreases as the distance to the wall decreases, and this attenuation effect is increasing with the frequency.

A method for BLA prediction in turbulent pipe flows is proposed on the basis of 1D conduction calculations using an "effective" thermal diffusivity in the sodium.

NOMENCLATURE

D	diameter of the pipe
Pe	Peclet number
Pe*	local Peclet number
Q	flowrate
R	radius of the pipe
Re	Reynolds number
T	temperature
U	velocity
U*	friction velocity
x	axial distance
y	distance to the wall
α	thermal diffusivity
α'	effective thermal diffusivity
ΔT	temperature difference
θ	temperature fluctuation amplitude

Subscripts

c	cold
h	hot
T	total
w	wall

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TESTS	Q_h m^3/h	Q_c m^3/h	Q_T m^3/h	T_h °C	T_c °C	ΔT °C	U_h m/s	U_c m/s	U_h/U_c	U_T m/s	Re	Pe
1	153	17	170	400	350	50	1,4	0,47	3	1,5	$9,2.10^5$	4600
2	90	10	100	400	350	50	0,83	0,27	3	0,88	$5,4.10^5$	2700
3	59,4	6,6	66	480	330	150	0,55	0,18	3	0,58	$3,6.10^5$	1800
4	119	20	139	400	348	52	1,1	0,55	2	1,23	$7,5.10^5$	3800
5	59,6	20	79,6	400	350	50	0,55	0,55	1	0,7	$4,3.10^5$	2200
6	19,8	2,2	22	400	380	20	0,18	0,06	3	0,19	$1,2.10^5$	600
7	29,8	20	49,8	430	353	77	0,271	0,55	0,5	0,44	$2,7.10^5$	1350

Table 1 : Test characteristics

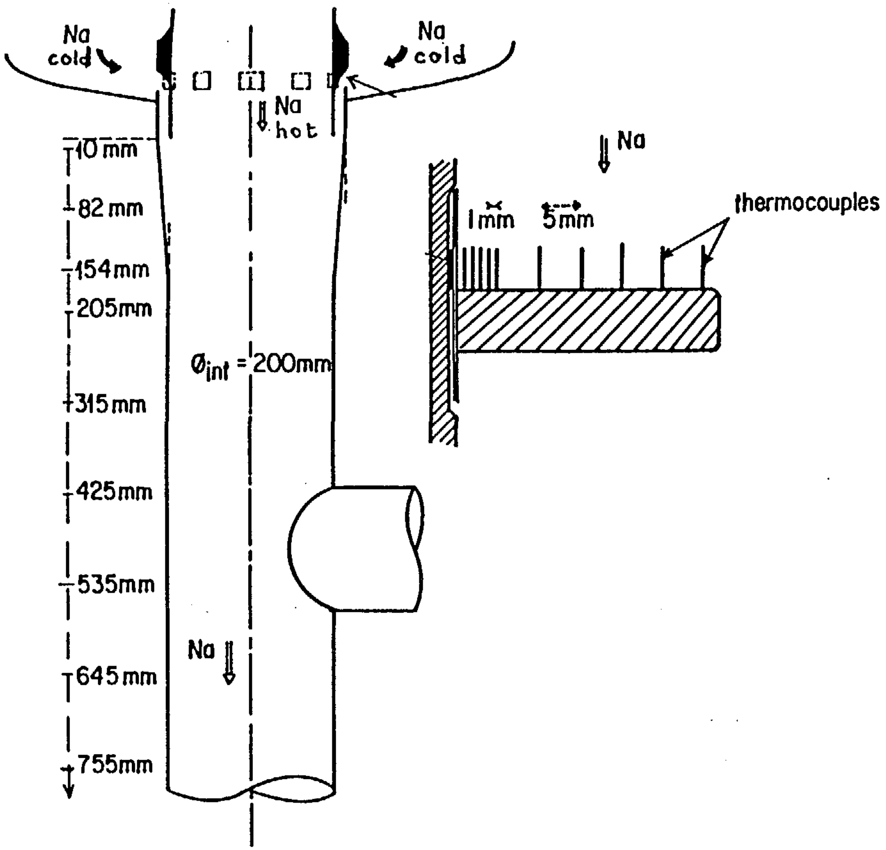

Fig. 1 : Test section

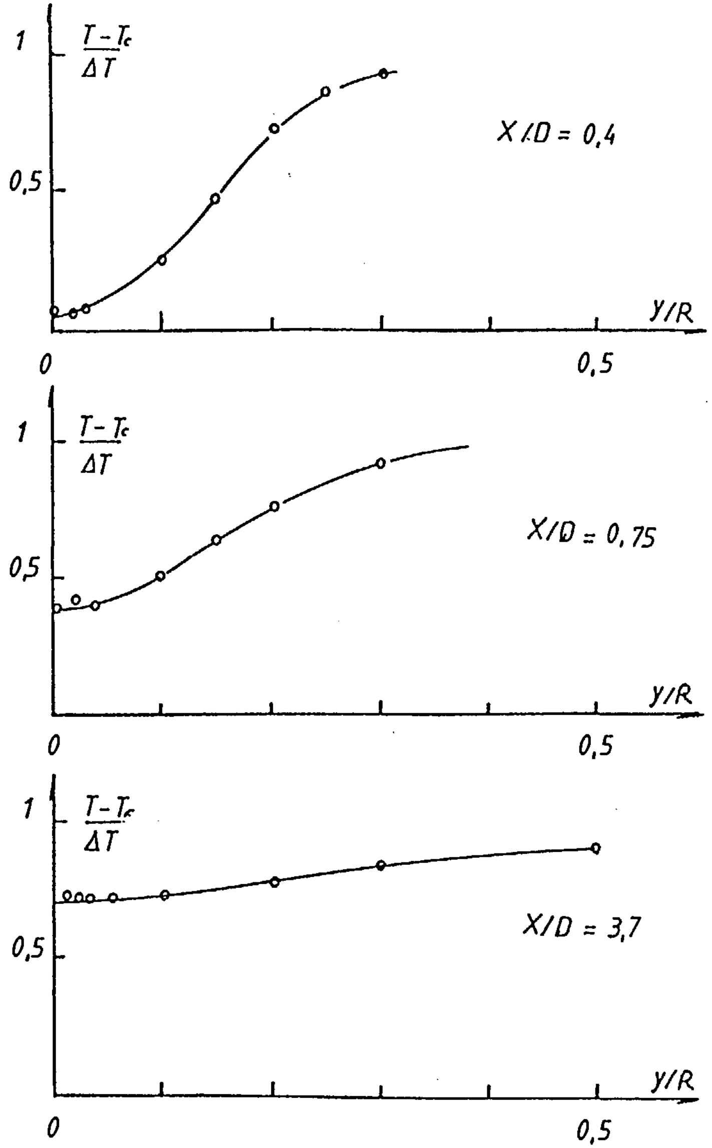

Fig. 2 : Mean temperature

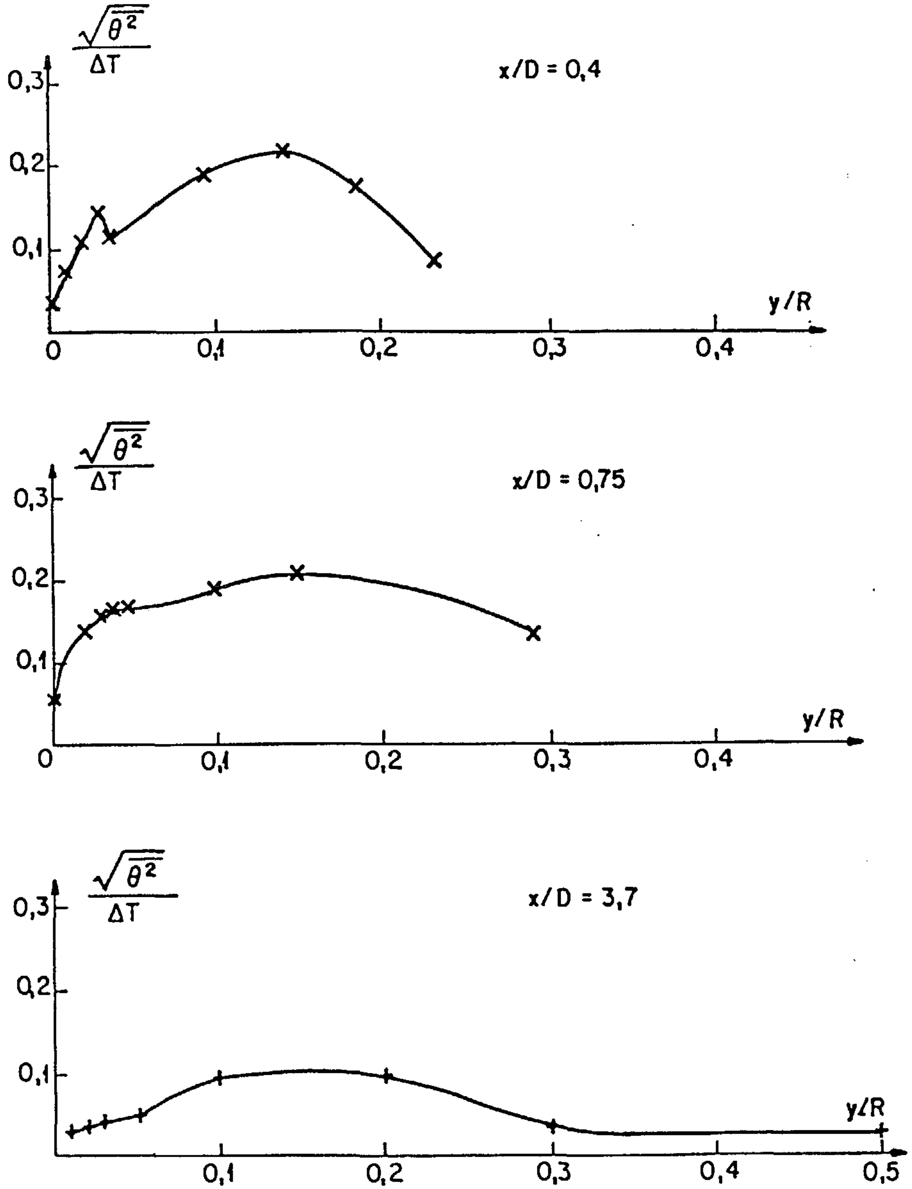

Fig. 3 : rms of temperature fluctuations

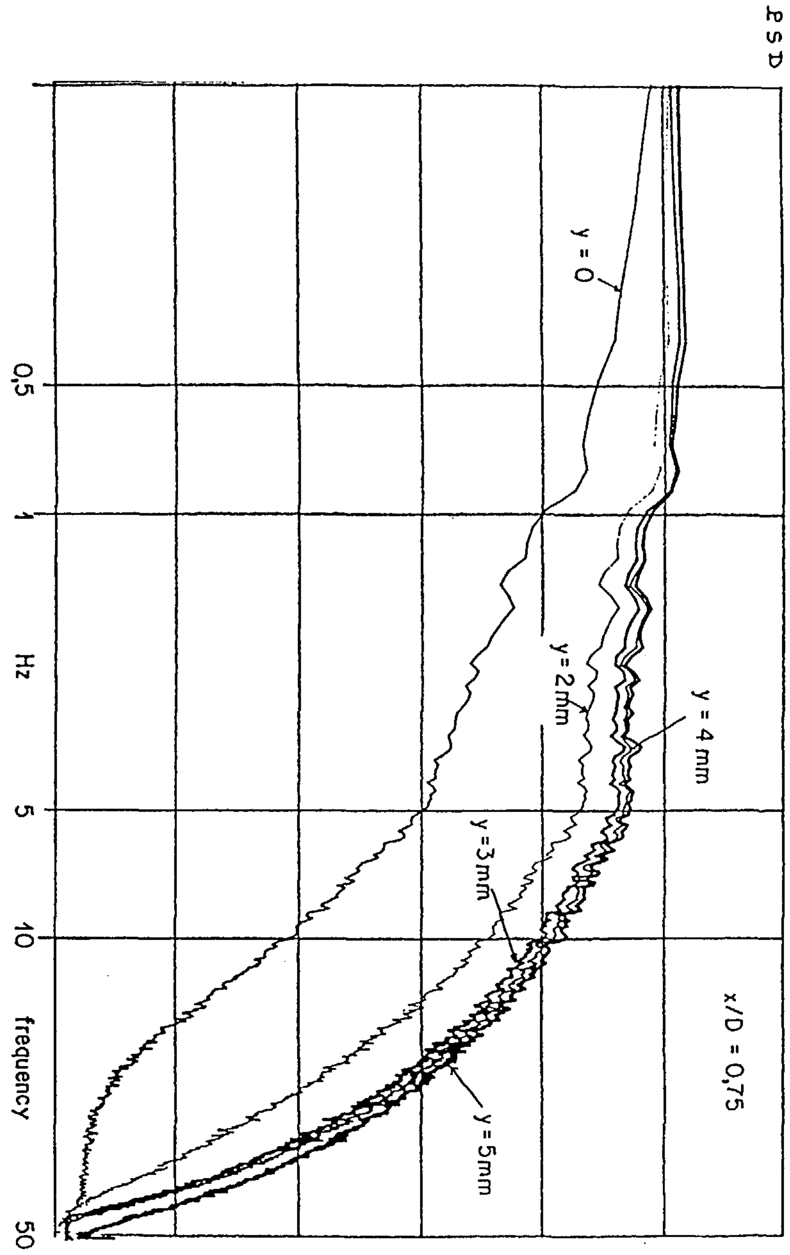

Fig. 4 : PSD of temperature fluctuations

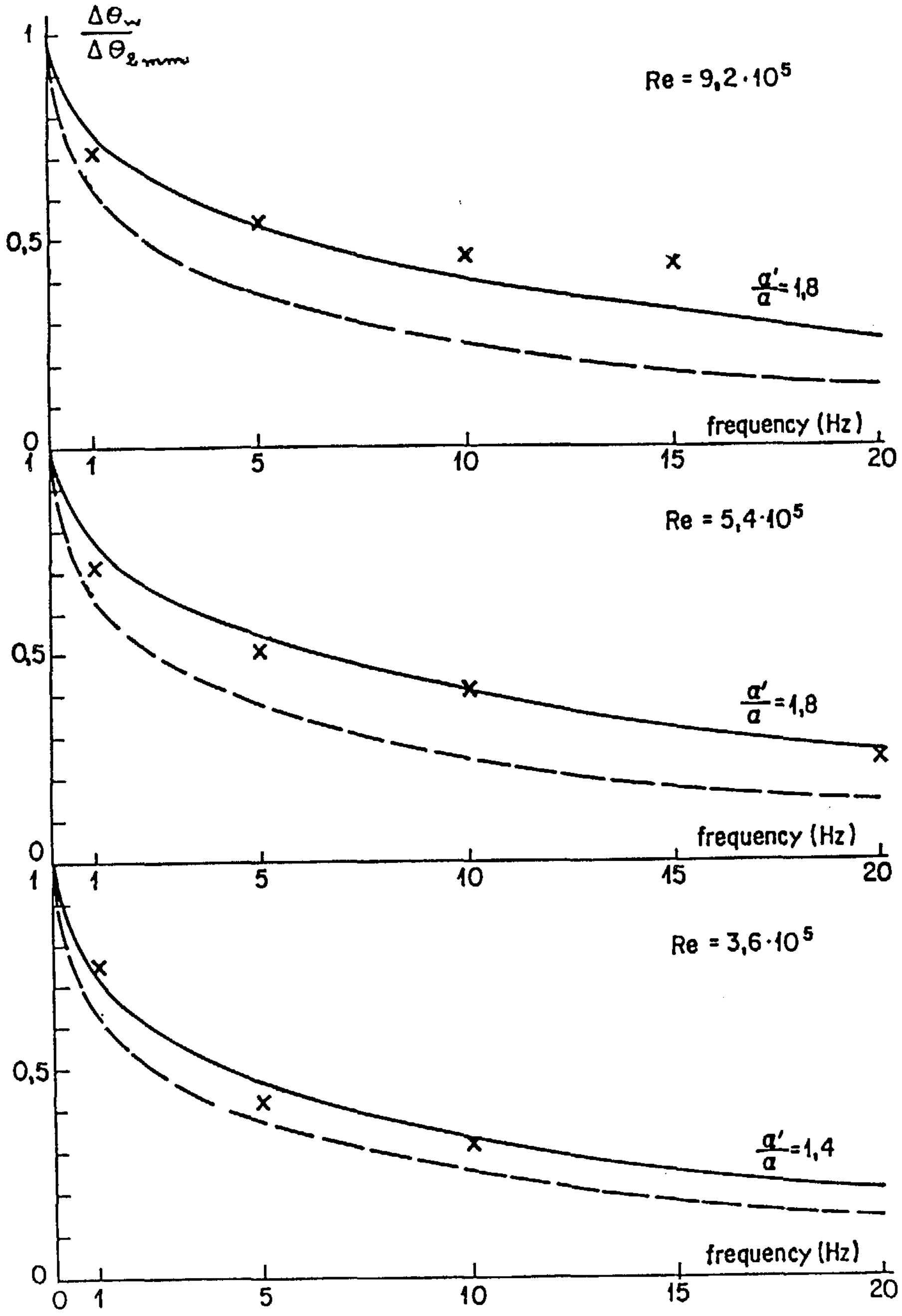

Fig. 5 : Wall to fluid fluctuations amplitude

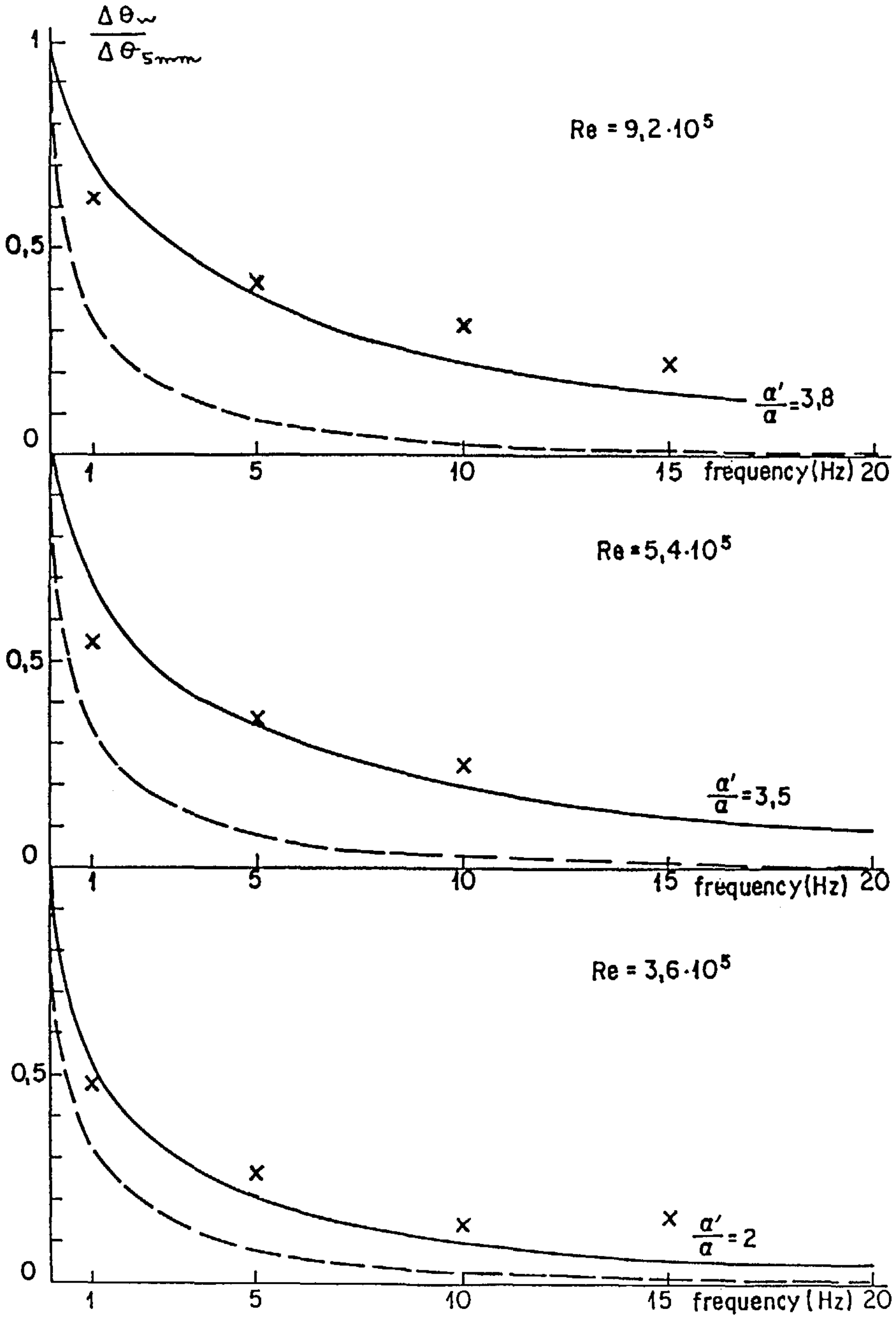

Fig. 6 : Wall to fluid fluctuation amplitude

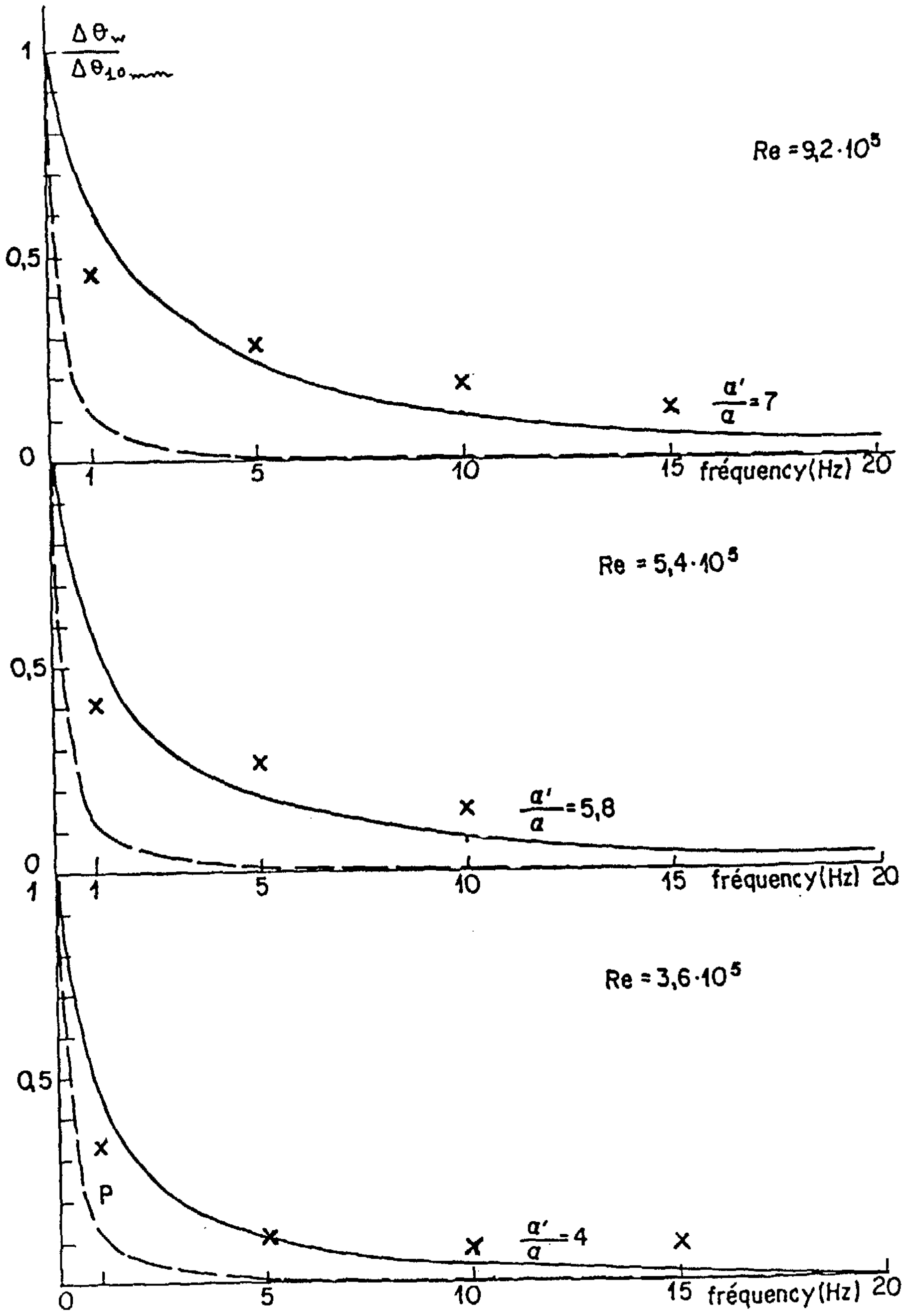

Fig. 7 : Wall to fluid fluctuation amplitude

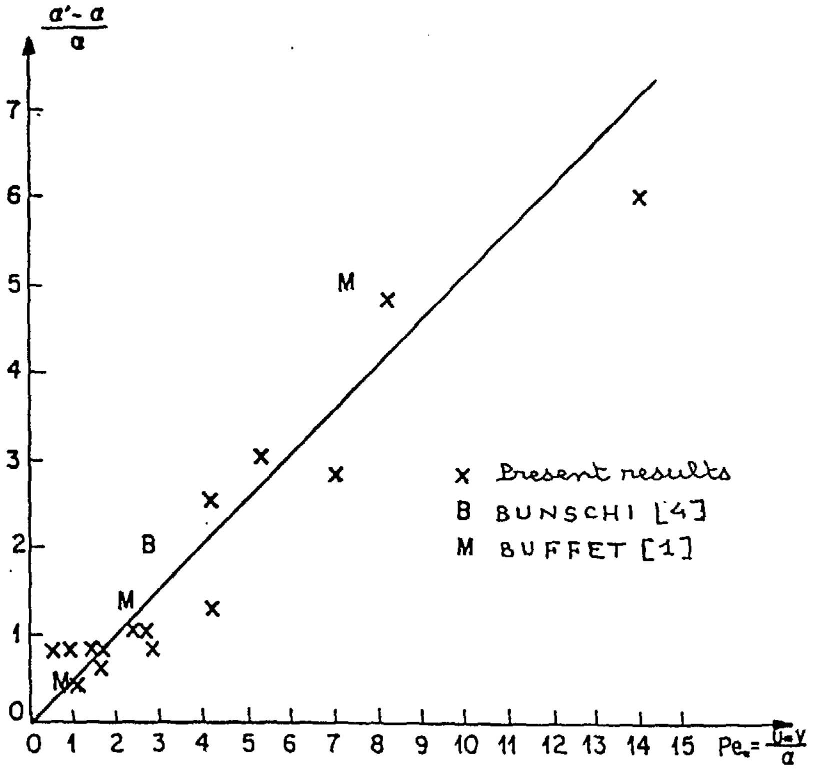

Fig. 8 : Effective thermal diffusivity