THE INFLUENCE OF INFRARED RADIATION ON THE NATURAL CONVECTION BOUNDARY LAYER

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ABSTRACT

The calculation of the infrared absorption in humid air (Schenker et al. 1995) has suggested an influence on the temperature and velocity profiles of the natural convection boundary layer. The profiles have been measured and confirm a small effect on the profiles in the laminar region of the flow but a strong one on the transition from laminar to turbulent flow.

In a first approach based on the analytical solution for the conduction regime expressions could be deduced showing at least qualitatively the same modification of the temperature and the velocity profiles as measured. They will be used for the stability analysis of the laminar flow.

KEYWORDS

Infrared radiation, humidity, boundary layer, stability

INTRODUCTION

It has become common use to compute air flow fields in rooms by sophisticated CFD-programs for answers to problems of comfort, heat transfer etc..Most of them consider only the convectional interaction of the flow field with the room boundaries, mostly by means of approximations as the $k-\varepsilon$-models (Ludwig et al. 1989; Hinze 1975). Only a few take into account in a second step the infrared radiation field (Behnia et al. 1990).

A closer look at the absosorption spectra of water vapor (Rothman et al 1987) (Figure 1) however, shows the effects to be expected:

- a non negligable magnitude of absorbed power.
- a very local distribution of absorbed power due to the sharp deep lines of the water vapor spectra.

In a first step the authors (Schenker et al. 1995) have shown by means of computational simulation using the high resolution spectra of water (Figure 1) that the magnitude of absorbed power is not negligeable and that local effects should be observed (Figure 2).

The main absorption is concentrated in a thin air layer corresponding approximately to the boundary layer of natural convection in a room.

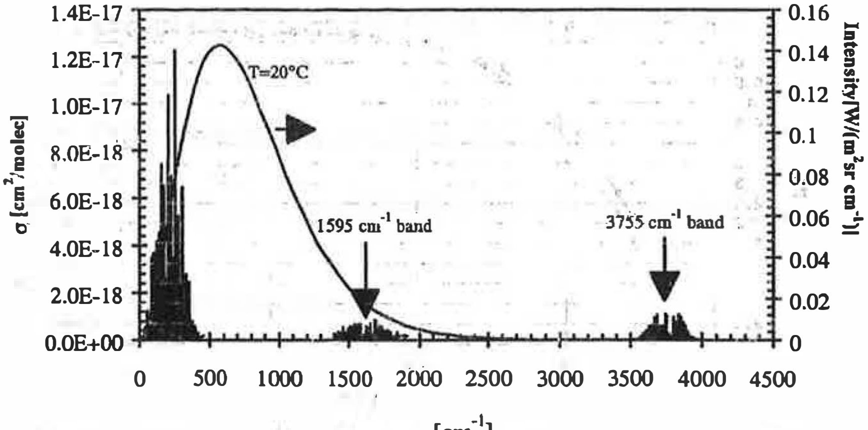

Figure 1 Absorption spectra of water vapor combined with the spectral intensity of a black-body at a temperature of T_b=20°C.

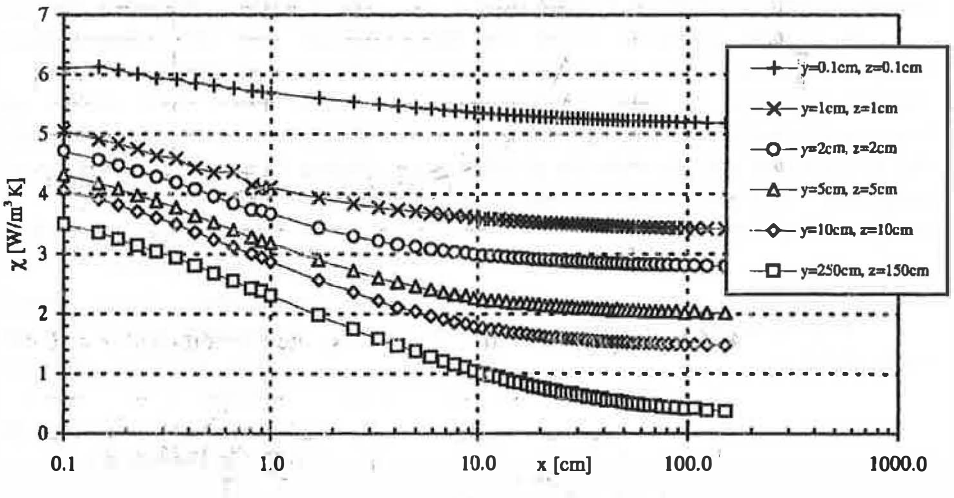

Figure 2 Local specific heat absorption due to radiation as a function of the wall distance for air temperature T_g=293 K, wall temperatures T_w=298 K and relative humidity f_{rel}=50%

In a second step (Brändli et al. 1996) the temperature and velocity profiles were measured under different conditions (water vapor pressure of about 1000 Pa and 3000 Pa).

The experimental results showed:

- a small influence on the temperature and the velocity profiles in the laminar region of the flow (Figure 3 and 4).
- an influence on the critical transition from laminar to turbulent flow (Figure 5).

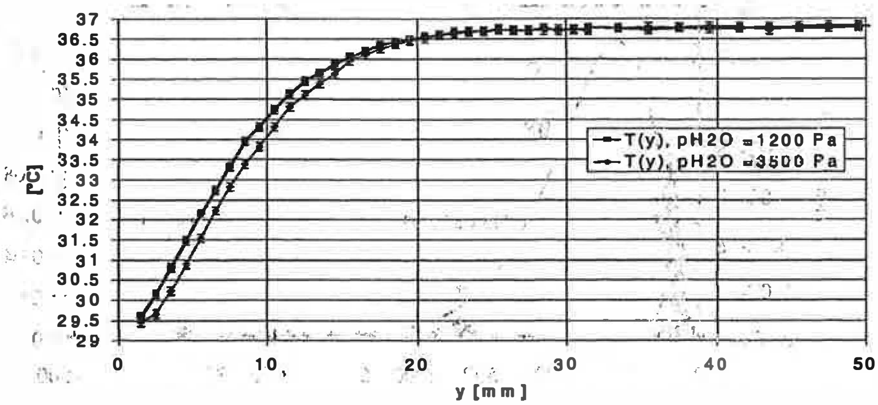

Figure 3 Temperatur profiles with different absolute h midities at z = 50 cm

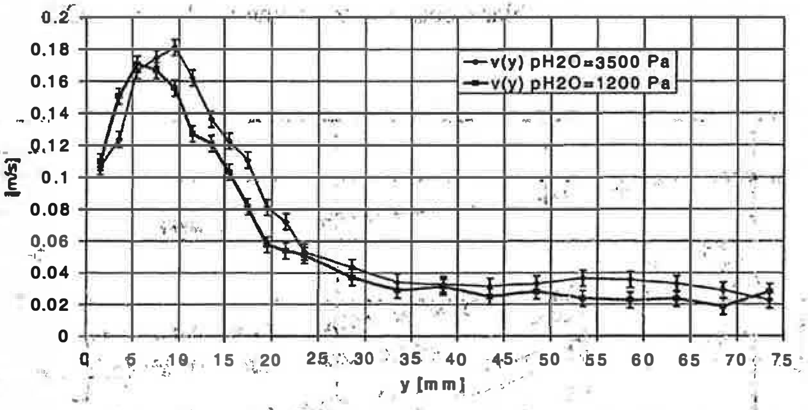

Figure 4 Velocity profiles with different absolute humidities at z = 50 cm

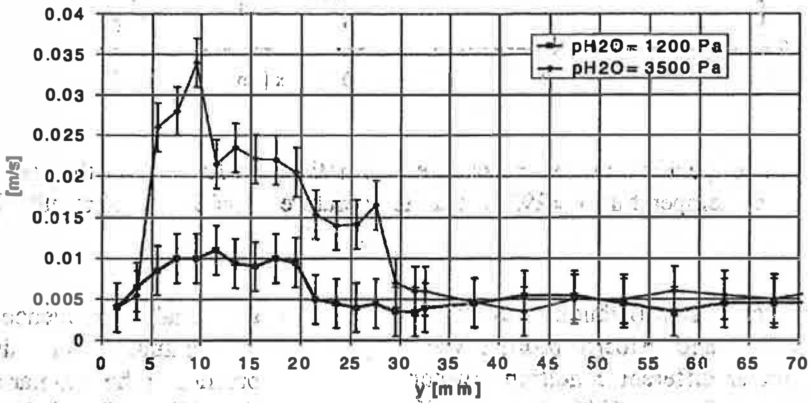

Figure 5 Standard deviation of velocity profiles with different absolute humidities,

z = 200 cm

Therefore the stability of the laminar flow under infrared radiation impact has to be investigated. The equations however, even for natural convection on a vertical plate have up to now no analytical solution, which is required for the stability analysis. In a first step we therefore used the available analytic solution for the conduction regime, e.g. the state at very early times of the flow development for the inclusion of the radiation source term.

FIRST ANALYTICAL RESULTS

Schetz and Eichhorn (1962) solved the equations of the natural convection on a vertical plate for the conduction regime where the horizonal velocity component vanishes (equation 1).

This regime describes the flow for small times (Siegel et al. 1958) just after the plate has been raised to a higher temperature.

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} + g\beta\Delta T\vartheta$$
$$\frac{\partial \vartheta}{\partial t} = a \frac{\partial^2 \vartheta}{\partial y^2} \qquad (1)$$

whit u= vertical velocity component

$\vartheta = \frac{(T - T_\infty)}{\Delta T}$ $\Delta T := (T_w - T_\infty)$

a= thermal conductivity

ν= kinematic viscosity

β=isobaric thermal volume expansion coefficient

These equations are now solved with a heat source representing the infrared absorption due to the water vapor. The equation 1 transforms then to:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} + g\beta\Delta T\vartheta$$
$$\frac{\partial \vartheta}{\partial t} = a \frac{\partial^2 \vartheta}{\partial y^2} + re^{-\alpha y} \qquad (2)$$

where α and r are parameters determined from our computational simulations (Schenker et al. 1995).

By means of Laplace transforms one gets analytical time dependent solutions for the temperature and the velocity profile:

$$(T(y,t) - T_\infty) = \Delta T \,\mathrm{Erfc}[z] - \frac{1}{g\beta}\frac{re^{-\alpha y}}{a\alpha^2}\left(1 - e^{a\alpha^2 t}\right)$$
$$- \frac{1}{g\beta} r\left(\frac{e^{a\alpha^2 t}}{2a\alpha^2}\left(e^{-\alpha y}\mathrm{Erfc}[z - \alpha\sqrt{a\,t}] + e^{\alpha y}\mathrm{Erfc}[z + \alpha\sqrt{a\,t}]\right) - \frac{1}{a\alpha^2}\mathrm{Erfc}[z]\right) \qquad (3)$$

$$u(y,t) = \frac{re^{-\alpha y}}{a^2\alpha^4}\left(\frac{1}{Pr} + \frac{1}{1-Pr}e^{a\alpha^2 t} - \frac{1}{Pr(1-Pr)}e^{aPr\alpha^2 t}\right) + \frac{1}{1-Pr}\left(\vartheta_0 + \frac{r}{a\alpha^2}\right)\left((t + 2z^2 t)\mathrm{Erfc}[z] - \frac{2zt}{\sqrt{\pi}}e^{-z^2}\right)$$
$$- \frac{1}{1-Pr}\left(\vartheta_0 + \frac{r}{a\alpha^2}\right)\left(\left(t + \frac{2z^2 t}{Pr}\right)\mathrm{Erfc}\left[\frac{z}{\sqrt{Pr}}\right] - \frac{2zt}{\sqrt{\pi Pr}}e^{-\frac{z^2}{Pr}}\right)$$
$$+ \frac{r}{(1-Pr)a^2\alpha^4}\left(\mathrm{Erfc}[z] - \frac{1}{2}e^{a\alpha^2 t}\left(e^{-\alpha y}\mathrm{Erfc}[z - \alpha\sqrt{a\,t}] + e^{\alpha y}\mathrm{Erfc}[z + \alpha\sqrt{a\,t}]\right)\right) \qquad (4)$$
$$- \frac{r}{Pr(1-Pr)a^2\alpha^4}\left(\mathrm{Erfc}\left[\frac{z}{\sqrt{Pr}}\right] - \frac{1}{2}e^{aPr\alpha^2 t}\left(e^{-\alpha y}\mathrm{Erfc}\left[\frac{z}{\sqrt{Pr}} - \alpha\sqrt{aPr\,t}\right] + e^{\alpha y}\mathrm{Erfc}\left[\frac{z}{\sqrt{Pr}} + \alpha\sqrt{aPr\,t}\right]\right)\right)$$

where $Pr = \frac{\nu}{a}$ (Prandtl Number)

$\vartheta_0 = g\beta\Delta T$

$z = \frac{y}{2\sqrt{at}}$

The resulting profiles developing after a certain time are shown in Figure 6 and Figure 7. They show an effect similar to the one measured (Figure 3, Figure 4).

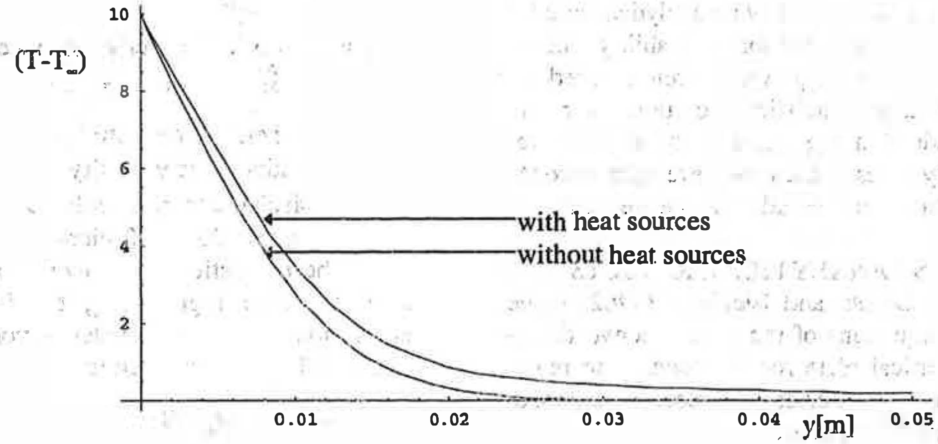

Figure 6 Temperature profiles after 2 s with and without heat sources

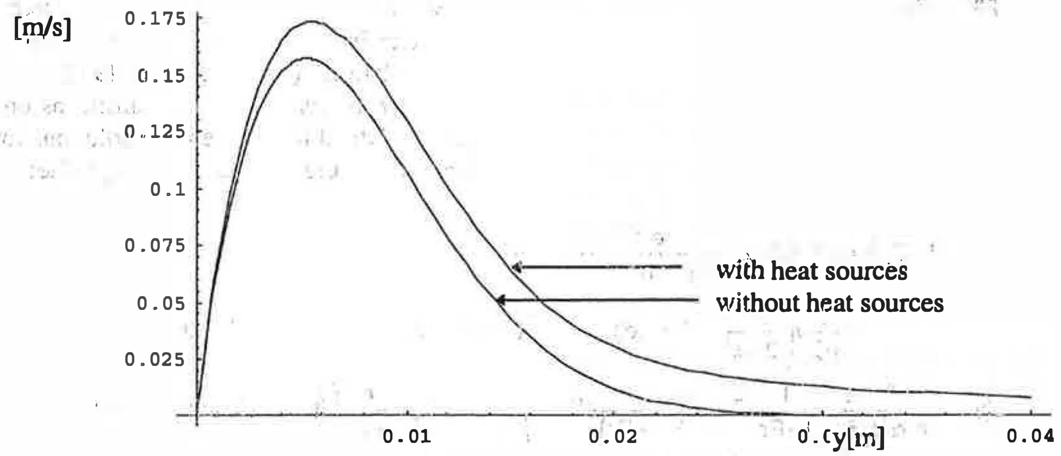

Figure 7 Velocity profiles after 2 s with and without heat sources

DISCUSSION

First analytical solutions of the conduction regime of the flow corresponding to the early state of the natural convection flow show at least qualitatively the same effect as the profiles measured. Therefore these solutions will be examined in further detail to obtain a base for the investigation of the stability of the laminar natural convection flow.

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