SIMULATION OF THERMAL COUPLING BETWEEN A RADIATOR AND A ROOM WITH ZONAL MODELS

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ABSTRACT

Zonal models are a promising way to predict air movement in a room with respect to comfort conditions and gradient of temperature because they require extremely low computer time and may be therefore rather easily included in multizone air movement models.

The main objective of this paper is to study the arbility of the zonal models to predict the thermal behaviour of air in case of natural convection coupled with a radiator. First, we present two zonal models available in the literature. In that way, we describe the main hypotesises of the Howarth two zone model and the five zone model proposed by Inard. A first validation on a experimental comparison is presented.

With the support of the IEA Annex 20 (Air flow pattern within buildings) testcase, we compare the results of the models. Furthermore, a comparison is made with the results of Chen obtained by simulation with a Low Reynolds number K-e model. First, it appears that all zonal models give indoor air temperature profiles consistent with Low Reynolds number k-e e results.

INTRODUCTION

The objective of this paper is to demonstrate the ability of zonal models to predict the thermal behaviour of air in a room heated by a radiator.

The first studies on zonal models are due to the University of Liège (Lebrun 1970 ; Laret 1980 ; Ngendakumana 1988). The basic assumption of such models is to split the indoor air volume of a heated room in several zones. These zones are coupled together considering the heat and mass transfers. The arbitrary division of the indoor volume into elementary zones requires at first a knowledge of the different kind of flow we are supposed to find in a real case. Furthermore, writing continuity and energy balance equations in each zone is not sufficient to ensure the closure of the problem. So, the identification of one or various conductances relative to the selected flow pattern is a necessary task. This task has to be realised by theoritical or experimental studies dealing with each classic configuration.

One of the main advantages of zonal models compared to others which consider uniformity of air temperature in each room is their ability to predict more accuratly heat transfers and thermal stratification with low computationnal times as a result of simplified assumptions on the airflow patterns occuring in the room.

This paper deals with two zonal models described in the literature :

- two zone model
- five zone model

For each one, we review their main hypothesises and we compare the results given on a experimental case. Then a comparison with higher-level model on a IEA Annex 20 testcase is shown.

LIST OF SYMBOL

Cp	:	specific heat capacity of air (J/KGK)
Hra	:	height of heat source (m)
H	:	height of the room (m)
Lc	:	length of cold wall (m)
Lra	:	length of heat source (m)
Pconv	:	convective power of heat source (W)
Tra	:	surface temperature of heat source (°C)
T	:	mean air temperature of the room (°C)
Vc	:	air mass flow rate of cold boundary layers (Kg/s)
φ_{wall}	:	convective heat flux of the vertical walls (W)
St	:	Stanton number
Tm(Z)	:	maximum air temperature of the plume at the altitude Z (°C)
Tw	:	surface temperature of window (°C)
Um(Z)	:	maximum air velocity in the plume at the altitude Z (m/s)
Z	:	altitude (m)
φ_{conv}	:	convective heat flux density (W/m2)

TWO ZONE MODEL

Method

This model is based on the studies of A.T. Howarth described in his thesis (Howarth 1980). The objective is to evaluate the temperature stratification in a room heated by a radiator with a simple model. This technique requires information and assumptions on the convective flows and heat transfers which occur in the room.

The assumptions of the basic model are the following:

- the radiator is entirely located beneath the window. The buoyant plume generated by the heat source rises along the window with which it exchanges heat and spreads under the ceiling.

- because of the temperature difference between the core and the walls, downward boundary layers develop along the cold vertical surfaces. The mass flow rates in these layers balance the radiator plume. The model calculates the heat exchange with all the walls of the room (the simulation is "tridimensional")

- in the core of the room, the temperature field depends only on the vertical coordinate.

The model determines a steady-state profile of temperature, defined by two temperatures : a upper zone temperature, located just under the ceiling and a lower zone temperature, located just above the floor. Thus, the model considers a subdivision of the room in two zones, separated by a neutral plane which is the horizontal plane accross which the net vertical volume flow rate is equal to zero.

The figure 1 gives a scheme of flow pattern.

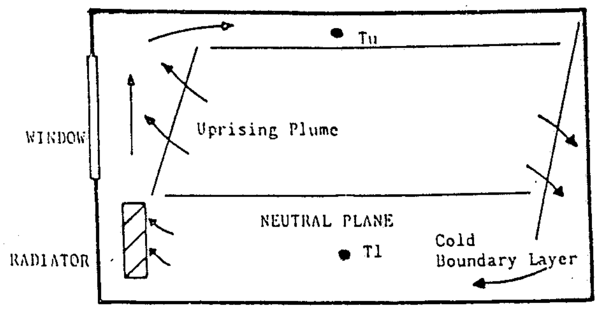

Figure 1 : Scheme of flow pattern for a two zone model

Model Description

The input data are the following :

- room, glazing and heater dimensions
- walls, ceiling and floor temperatures
- surface temperature of the heater or average temperature of the room, T

- Modelisation of the heater

The characteristics of the radiator and the generated plume are experimentally determined. The results of these experiments lead to general expressions for heat transfers between the radiator, the room and the cold surfaces, and flow characteristics of the developing heater plume.

The heat transfer between the heat emitter and the room is :

$$Pconv = 3.07\ (Tra - T)^{1.248} Hra^{0.75} Lra$$

The heat transfer from the radiator plume to the glazing is taken into account, considering a convection coefficient equal to 2.5 W/m2K and the temperature difference between air plume temperature leaving the radiator plume to a window is based on forced convection. The same value of the convection coefficient to the ceiling is adopted. Sensivity tests show that temperature profiles are not subordinate to this coefficient. But the radiator surface temperature and heat losses strongly depends on the value of this coefficient.

- Heat and mass exchange at the cold wall

The heat flow from the core of the room to the cold walls has been experimentally determined by Howarth as :

$$\varphi_{wall} = 1.66\,\Delta T^{1.25}\,H^{0.75}$$

and the mass flow rate Vc in the boundary layer due to natural convection along the wall is expressed in the form :

$$Vc = 0.0033\,\Delta T^{0.25}\,H^{0.75}\,Lc$$

with : ΔT temperature difference between the core and the wall

The heat transfer coefficient at the floor is taken equal to 1 W/m2K, which is consistent with the correlations presented by many authors.

A computer code has been devised in CSTB in order to solve this equations set.

Resolution process

Due to the dependancy of heat fluxes in upper and lower temperatures, the calculation is made through an iterative process. The following three steps are repeated until the convergence is achieved :

Step one : heat exchange between radiator and room
The heater surface temperature is determined by the balance equation between the convective heat output of the radiator and the heat losses at the vertical surfaces, the ceiling the floor and the glazing.

Step two : position of the neutral plane
The neutral plane is the horizontal surface across which the upward flow due to the heating convective plume is equal to the downward flow in the boundary layers along the cold vertical surfaces.

Step three : upper and lower temperatures
Generally, the neutral plane is located not far from the top of the radiator. So, the upper zone temperature is the temperature which achieves the balance between the heat emitted by the radiator and the heat losses throught the window, the ceiling and the heat exchange from the upper zone to the lower one into the downward boundary layers.

The model only deals with convective heat fluxes and mass flow rates. There is no radiation model into the Howarth's formulation.

FIVE ZONE MODEL

Model Description

The inside air volume is split into five isothermal zones, coupled with massic conductances. For the case of a radiator or a convector within a dwelling cell, experimental studies (Lebrun 1970 ; Howarth 1980 ; Ngendakumana 1988) showed that, in most cases, the air flows have a main circulation along the way radiator, trail ceiling, vertical walls, floor and radiator. So, the inside air volume is cut into five zones which each is representative of this circulation as shown :

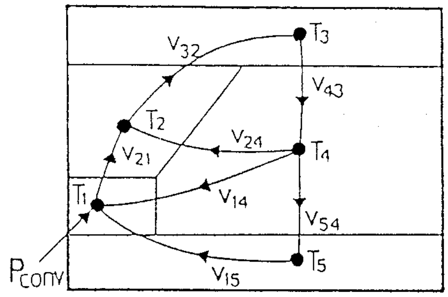

Figure 2 : Partition into five zones of a room heated by a radiator

For each zone, the mass and energy balances are written. The variables are the air temperature of the zones. To complete the description of the model, the radiator convective heating power, the different convective heat transfer coefficients and the massic conductances must be given or identified. For that an experimental program was built. The tests were performed in a climatic test room (Inard 1988) on different radiators and on one electric linear heat source. Two kinds of measurements were done :

- surface temperature inside and outside the walls, to measure conductive rates and compute radiative heat exchanges between walls and with the radiator.

- air temperature and air velocity in the plume, which were integrated to compute the air mass flow rate and the heat flow inside the plume.

- Experimental results

- Radiators convective heating power

From the experiment, it has been possible to express the radiator convective power as a function of the difference between the radiator surface temperature and the air temperature measured at the center of the cell and close to the floor. As an example, the figure 3 shows the experimental results obtained from four different single panel radiators and various mean water temperature.

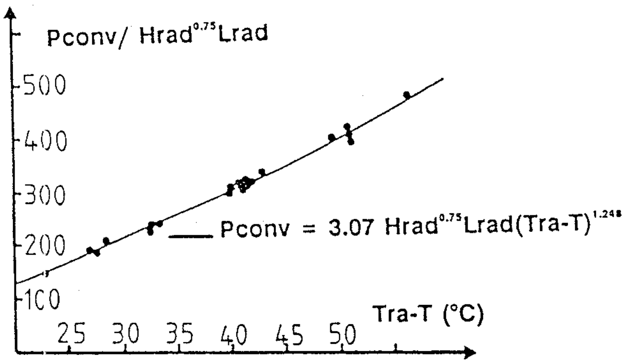

Figure 3 : Relationship between Pconv and ΔT for single pannel radiators.

The identified value of 1.25 is characteristic of laminar flow and compatible with the maximum value of Rayleigh number, based on radiator height, in the range of 2.109.

- Convective heat transfer to the walls

For the ceiling, the experimental values of heat exchange coefficient are shown :

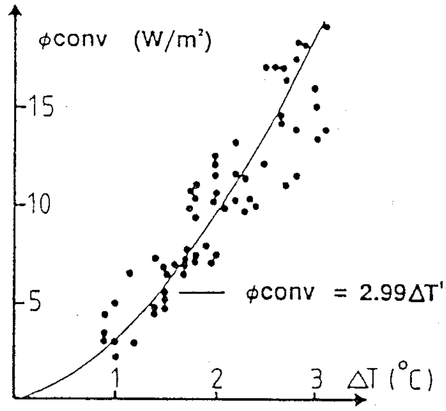

Figure 4 : Convective heat flux density at the ceiling

For the other surfaces (floor and vertical walls), we use literature results.(Lebrun 1970 ; Inard and Molle 1989)

Plume Characteristics

The experimental results show, on the one hand local similarity of velocity and temperature profiles, on the other hand that air mass flow rate in the plume of a radiator is similar to that of linear heat source. From an integral analysis of the plumes, the maximum velocity and temperature can be described.

The convective heat flux along the trail is expressed by the dimensionless Stanton number :

$$\varphi conv(Z) = Cp\left[Tm(Z) - Tw(Z)\right]Um(Z)\cdot\rho\cdot St$$

Experimental results have shown that Froude number, Stanton number reach constant values near the top of the radiators (around 0.4 m). Moreover, these values are independant of the type of radiator. So, and assuming that the wall in contact with the plume is isothermal, it is possible to express the mass flow rate and the convective heat flux along the trail. Therefore, the plume over the radiator has a complete description.

Radiant Heat Fluxes Calculation

The radiant heat fluxes are computed with the radiosity method. For simplicity, the view factors are computed with two assumptions :

- The radiator is cut into two surfaces : the front and the rear surface.

- The view factor between the radiator rear surface and the backwall is equal to the unity.

The knowledge of the radiosity of each surface enable us to calculate a radiant temperature at any point inside the room. The convective balance inside the room is computed with a radiative balance, by using an iterative process. Taking into account conduction inside the walls gives access to internal surface temperatures for given external conditions.

The calculation gives the radiator total heating power (total, convective and radiative rates), the internal surface temperatures and the air temperature of each zone.

COMPARISON WITH MEASUREMENTS

As a first validation, a comparison between zonal models simulation output and experimental data was made. These experiments were lead in a climatic chamber (Inard 1988). The dimensions of this room are 4m X 4m X 2.8m. It was heated by a radiator located beneath a window. The measurements are :

- the surface temperature of walls, ceiling, floor, window and heat source.

- the temperature profile at the center of the room.

- the total heat fluxes (radiative and convective) exchanged in the room

The figure 5 shows the comparison between calculated and measured vertical profile of temperature at the center of the room.

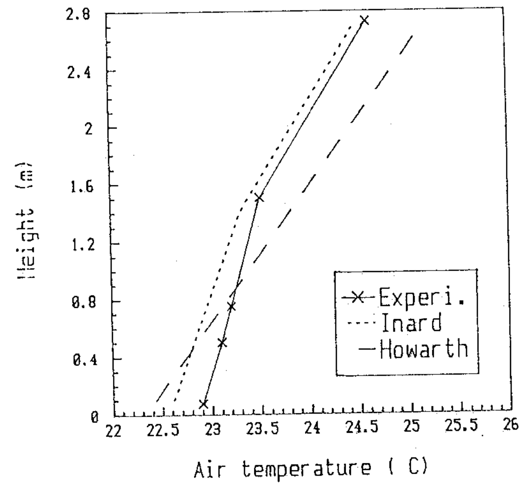

Figure 5 : Comparison with experimental data

COMPARISON ON A IEA ANNEX 20 TESTCASE

The objectives of the Annex 20 (Air Flow Patterns Within Buildings) of IEA is to valuate the performance of single and multi zone air and contaminant flows simulation techniques and to establish their viability as design tools. Considering these goals, zonal models seems to be especially adapted (Inard and Buty 1990).

In the frame of the subtask one of the annex, four testcases were defined. One of these concerned a room heated by a single pannel radiator located beneath a window. The figure 6 illustrates the three subtestcase considered.

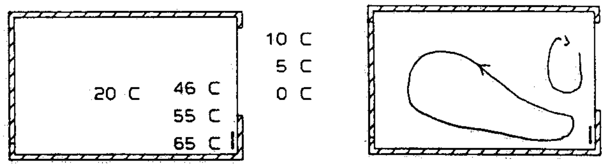

Figure 6 : IEA Annex 20 testcase D

A complete description of this testcase was made by T. Lemaire (Lemaire 1989).

Comparison of the Air Temperature Profiles

On the figure 7, we can see the air temperature profiles calculated by the zonal models. The upper and lower temperatures computed by the models have been arbitrarily located at 0.10 m from the corresponding horizontal surface (ceiling and floor). Furthermore, on these figures we have superimposed results obtained by simulation with a Low Reynolds number K-ε model (Chen 1990).

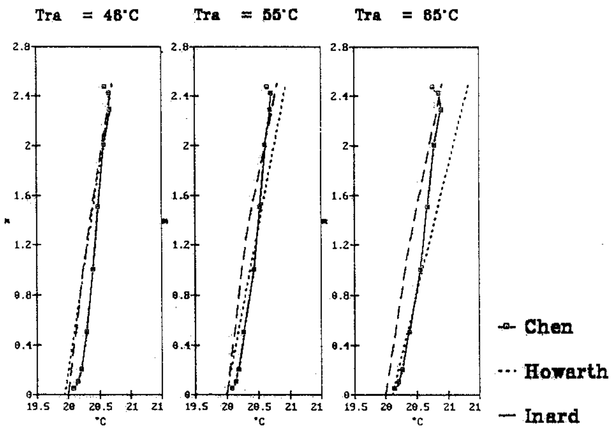

Figure 7 : Air temperature profiles

It appears that zonal models give air temperature profiles consistent with Low Reynolds number K-ε model results.

Comparison of Convective Heat Fluxes

On the figure 8 and 9, we give the convective heat fluxes for the heat source and the glazing.

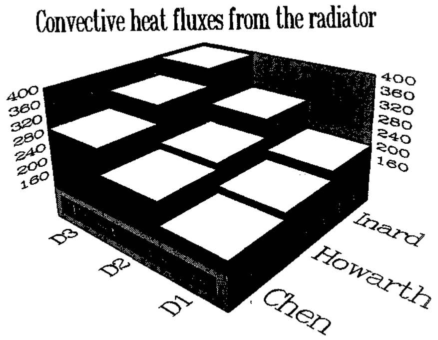

Figure 8

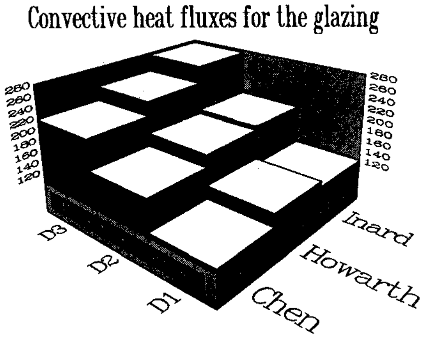

Figure 9

From these drawing we can see that the convective heat fluxes computed are of the same order of magnitude.

CONCLUSION

This study has shown the ability of zonal models to predict thermal stratification. The future development of these models will be :

- to take into account the other phenomena which influence room air flows like air change device or effect of opening doors

- to include the other kind of heat sources used in buildings (heating ceiling or heating floor for example)

All these studies will need experiments to validate the modelling approaches.

The low costs of such models allows to use them as design tools. It will permit, in the next future, to include them into multizone infiltration models to provide a better knowledge of the thermal behaviour of buildings.

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