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ABSTRACT

The paper describes a solving procedure which can predict the distribution of, for example, relative humidity in air conditioned rooms and cold stores. The procedure is based on the solution of six non-linear partial differential equations by a numerical method.

Cet article décrit un processus de résolution permettant de prédire la distribution de par ex. humidité relative dans des salles climatisées et des chambres froides. Cette méthode est fondée sur la résolution de six équations partielles différentielles non-linéaires par une méthode numérique.

Introduction.

The transfer of heat and moisture from various sources in air conditioned rooms and cold stores is governed by convection in the rooms. This transfer and removal can give rise to many combinations of air temperatures and humidities within the space. Certain of these combinations and the resulting surface temperatures may give condensation and must be avoided. A prediction of temperature and humidity fields will therefore be of interest in connection with the design of air conditioned rooms and cold stores.

The above parameters can be predicted by a method described in this paper, based on the solution of a set of equations for the flow by means of a numerical method.

Equations and numerical method.

It is supposed that the air movement in the section of the room under study may be regarded as steady and two-dimensional. This requirement does not exclude the use of several diffusers, which at first give a three-dimensional air movement, provided that the main body of air circulation, at a distance from the diffuser outlets, is steady and two-dimensional. In densely packed cold stores it is possible to examine small sections of the stores separately with the appropriate boundary conditions.

In practice the flow will be turbulent and the numerical method is based on solving the time-averaged differential equations employing one of the recently developed turbulence models. It consists of a transport equation for turbulent kinetic energy k, eq.(1), and an equation for the dissipation of turbulent kinetic energy ϵ, eq.(2). Equation (3) defines the turbulent viscosity μ_t in terms of the foregoing quantities.

$$\frac{\partial}{\partial x_1}\left(k\frac{\partial\psi}{\partial x_2}\right)-\frac{\partial}{\partial x_2}\left(k\frac{\partial\psi}{\partial x_1}\right)=\frac{\partial}{\partial x_1}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_2}\right)$$

$$+\mu_t\left[2\left(\left(\frac{\partial v_1}{\partial x_1}\right)^2+\left(\frac{\partial v_2}{\partial x_2}\right)^2\right)+\left(\frac{\partial v_1}{\partial x_2}+\frac{\partial v_2}{\partial x_1}\right)^2\right]-\rho_o\,\epsilon \qquad (1)$$

$$\frac{\partial}{\partial x_1}\left(\epsilon\frac{\partial\psi}{\partial x_2}\right)-\frac{\partial}{\partial x_2}\left(\epsilon\frac{\partial\psi}{\partial x_1}\right) = \frac{\partial}{\partial x_1}\left(\frac{\mu_t}{\sigma_\epsilon}\frac{\partial\epsilon}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(\frac{\mu_t}{\sigma_\epsilon}\frac{\partial\epsilon}{\partial x_2}\right)$$

$$+c_1\mu_t\left[2\left(\left(\frac{\partial v_1}{\partial x_1}\right)^2+\left(\frac{\partial v_2}{\partial x_2}\right)^2\right)+\left(\frac{\partial v_1}{\partial x_2}+\frac{\partial v_2}{\partial x_1}\right)^2\right]\frac{\epsilon}{k}-c_2\rho_o\frac{\epsilon^2}{k} \qquad (2)$$

$$\mu_t = c_\mu\,\rho_o\,\frac{k^2}{\epsilon} \qquad (3)$$

ψ is the stream function, v_1 and v_2 mean velocities. The factors σ_k, σ_ϵ, c_1, c_2 and c_μ are various constants. The development of the equations is described more explicitly by Launder et al [1] .

The transport equation for vorticity ω is derived from the Navier-Stokes equations, while stream function ψ and ω are related by definition.

$$\frac{\partial}{\partial x_1}\left(\omega\frac{\partial\psi}{\partial x_2}\right)-\frac{\partial}{\partial x_2}\left(\omega\frac{\partial\psi}{\partial x_1}\right) = \frac{\partial}{\partial x_1}\left(\frac{\partial\mu_t\omega}{\partial x_1}\right)$$

$$+\frac{\partial}{\partial x_2}\left(\frac{\partial\mu_t\omega}{\partial x_2}\right)+\rho_o\,\beta\,g_2\frac{\partial T}{\partial x_1} \qquad (4)$$

$$\frac{\partial}{\partial x_1}\left(\frac{1}{\rho_o}\frac{\partial\psi}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(\frac{1}{\rho_o}\frac{\partial\psi}{\partial x_2}\right) = -\omega \qquad (5)$$

ρ_o, β and g_2 denote density, coefficient of volume expansion and gravitational acceleration respectively. T is the temperature.

The thermal energy equation (6) and the mass conservation equation (7) complete the formulation:

$$\frac{\partial}{\partial x_1}\left(T\frac{\partial\psi}{\partial x_2}\right) - \frac{\partial}{\partial x_2}\left(T\frac{\partial\psi}{\partial x_1}\right) = \frac{\partial}{\partial x_1}\left(\frac{\mu_t}{\sigma_h}\frac{\partial T}{\partial x_1}\right)$$

$$+ \frac{\partial}{\partial x_2}\left(\frac{\mu_t}{\sigma_h}\frac{\partial T}{\partial x_2}\right) \qquad (6)$$

$$\frac{\partial}{\partial x_1}\left(m_w\frac{\partial\psi}{\partial x_2}\right) - \frac{\partial}{\partial x_2}\left(m_w\frac{\partial\psi}{\partial x_1}\right) = \frac{\partial}{\partial x_1}\left(\frac{\mu_t}{\sigma_w}\frac{\partial m_w}{\partial x_1}\right)$$

$$+ \frac{\partial}{\partial x_2}\left(\frac{\mu_t}{\sigma_w}\frac{\partial m_w}{\partial x_2}\right) \qquad (7)$$

where m_w is the mass fraction, the mass of water vapour pr. unit mass of mixture. σ_w and σ_h are the turbulent Schmidt and Prandtl numbers respectively.

In all the equations the viscosity μ is ignored, because it is small compared to turbulent viscosity μ_t and the molecular exchange coefficients are ignored because they are small compared to the turbulent exchange coefficients of heat μ_t/σ_h and of mass μ_t/σ_w.

The six differential equations (1), (2), (4), (5), (6) and (7) containing the six unknown factors ω, ψ, T, m_w, k and ϵ represent a complete description of the air flow, and they form the basis of the numerical solution method.

In cases of small temperature differences and high velocities the buoyancy term in the vorticity equation (4) will vanish. The temperature will not influence the other factors, except, in certain cases, the boundary conditions of the mass fraction. Ignoring these effects it is then possible to use the similarity between equation (6) and equation (7) and compare distributions of temperature and mass fraction, as described later.

In the numerical method the section under study is divided into a number of elements surrounding mesh points. The differential equations are replaced by a set of finite difference equations at each point, and these equations are solved by a modified Gauss iteration.

The development of the difference equations and the structure of the iterative procedure are described in detail by Gosman et al [2].

Temperature and mass distribution in a room.

Fig. 1 shows the comparison between a measured and a predicted temperature or mass profile. The profile is measured as the temperature distribution in a model experiment. The boundary conditions are as follows: Specified constant heat flux at the lower horizontal surface. Three other surfaces isolated. Dimensions and flow can be characterised by

$$L/H = 3.0, \quad h/H = 0.056, \quad Re = 7100$$

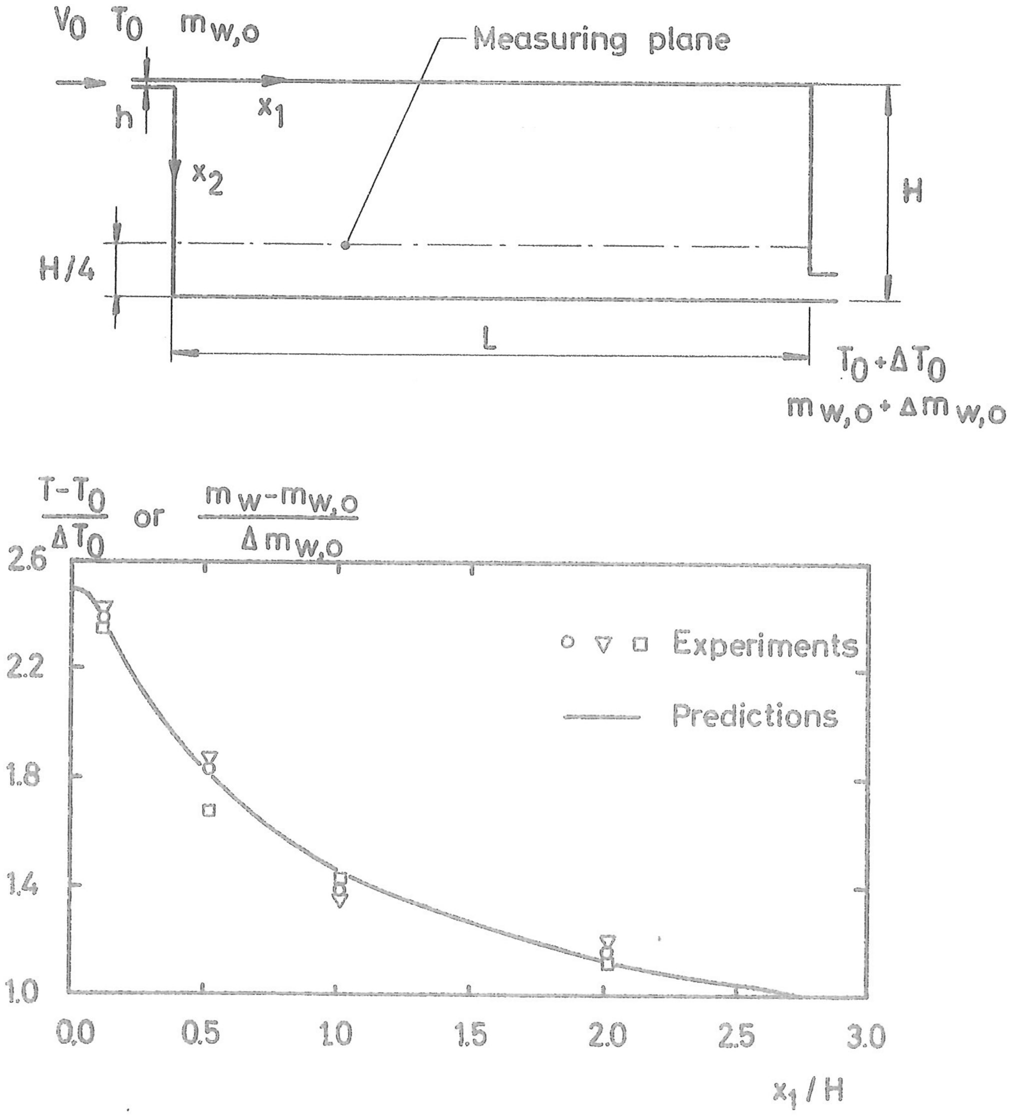

FIG. 1

Comparison between predicted and measured temperature or mass distribution. $h/H = 0.056$, $L/H = 3.0$ and $Re = 7100$.

where L, H, and h is length of model, height of model and height of diffuser opening respectively, see figure 1. The Reynolds number Re is based on diffuser velocity V_o and height h. Further details on the model tests are given in reference [3].

Temperature and mass fraction are made dimensionless by the diffuser inlet values T_o and $m_{w,o}$. ΔT_o and $\Delta m_{w,o}$ are the differences between inlet and outlet values, see fig. 1.

The predicted results are solutions of transport equations of the type (6) and (7). It is supposed that the - per unit area - flow of heat and mass through the lower boundary are constant, and not coupled. The velocity induced by the mass flow from the boundary is ignored.

It will be seen that the prediction gives a satisfactory profile over the whole area. From the values given on fig. 1 it is possible to predict the distribution of relative humidity φ in an air conditioned room. A person in thermal comfort e.g. at an activity level of 1o2 W, evaporates 42 g/h relatively independent of air temperature, and has a convective heat loss of e.g. 47 W, see Fanger [4]. If the boundary values at the floor in fig. 1 represent a uniform distribution of a known number of people, ΔT_o and $\Delta m_{w,o}$ can be found at the given V_o. From these values, and the values at the diffuser, T_o and $m_{w,o}$, it is possible to calculate the actual temperature and mass fraction profiles and hence to obtain the distribution of relative humidity φ.

It should be emphasized that the results of fig. 1 are only valid for the diffuser dimension h/H = o.o56. A smaller and more characteristic dimension, e.g. $h/H = 0.005$ see [5], gives higher entrainments in the recirculating flow and therefore a more uniform distribution of the temperature and mass fraction in the occupied zone.

If the only source of heat and water vapour in a room is persons, the above mentioned prediction of relative humidity φ, will show a relatively constant value within a room. The reasons are, that both temperature and mass fraction are high or low at the same locations. When other heat sources are present, which are big compared to heat loss from the persons, the variations in mass fraction - or vapour pressure - are normally ignored.

Conclusion.

Comparison with test results shows that the suggested method of prediction is suitable for investigation of the humidity distribution in air conditioned rooms and cold stores.

Earlier work [3], [5] shows how the prediction method also gives the required information for evaluation of thermal comfort. This includes air velocity, air temperature, surface temperature, velocity and temperature gradients, and turbulence intensity.

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