PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

10th AIVC Conference, Dipoli, Finland
25-28 September, 1989

Paper 3

TRENDS IN AIRFLOW DESIGN AND MANAGEMENT, - CONTRIBUTIONS BY IEA ANNEX 20

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SYNOPSIS

What does the designer of a future energy-efficient building ask of the air flow specialist? - Static predictions of air flow patterns and optimization of thermal comfort and indoor air quality at design conditions will not be enough for him.

The paper suggests that time-dependent air flow simulation is imperative to respond to tomorrow's design needs. Different physical time scales for air flow patterns in spaces will be discussed. Heat capacity by components, different types of heat transfer, varying occupancy, control inputs etc. give rise to disparate time scales. The trend toward occupant controlled ventilation will continue. Air flow will interactively be adjusted to changing needs in each room. The IEA Annex 20 examines tools to predict steady air flow patterns within buildings. The dynamic management of air flows will require new methods that build on Annex 20 work.

1. INTRODUCTION

The air flow in a building is not stationary: People move around or enter rooms, ventilation is turned on or off, sudden sunshine triggers a thermal updraft, or a window is opened. In addition, new ventilation designs allow the occupant to interact with the system and to control location and volume of fresh air supply. Advanced air heating systems distribute hot air with a rotating nozzle and innovative schemes "shoot" lumps of fresh air as vortex rings at the occupant[1]. From the point of view of HVAC control, the indoor air, including supply and return flows, is a component of a dynamic system.

These examples suggest that the air flow pattern in a building is unsteady and that only transient computer simulation is suitable for its prediction.

Why do many of today's methods still simulate steady flow fields only? In particular some of the more complex numerical models for single room or multi-zone air flows aim at steady-state solutions.

Here are two possible answers:

(1) Numerical complexities of time-dependent simulation

(2) The phenomenon of interest can often be considered steady after a careful comparison of the relevant time scales of the actual problem.

The first answer applies to applications that are already complicated in their static description and require a great amount of computer time and resources. A single-room air flow pattern may easily require a 20x20x20 spatial resolution resulting in 8000 memory locations for each variable. If in addition the information for a few hundred time steps must be calculated and stored, along with time-dependent boundary conditions, the amount of data becomes overwhelming.

The same is true for multi-cell simulations where the solution of a large system of coupled equations to determine the steady-state pressure at each of, say, a hundred nodes (i.e., rooms or zones of rooms) is already a delicate task.

Many numerical methods take advantage of a time-marching procedure to asymptotically reach a steady-state solution from an arbitrary initial guess. However, during this process of convergence the boundary conditions are kept constant, and very often the transient solutions at finite times are not of interest.

With regard to explanation (2) above, experience has shown that many air flow patterns of practical interest can be analyzed by just looking at steady solutions at much reduced expense of computer resources. But this approach requires prior knowledge of the relevant time scales of the problem.

This is illustrated by the following example: At time $t = 0$ the air in a room of dimensions L is at rest. How long does it take to get the air moving when it is driven by the momentum of a jet of velocity u_o and mass flow $\dot{m}$ entering through a nozzle of diameter h ?

Several simplifications will be made: Instead of accounting for friction, a relation proposed by Nielsen[2] is used to estimate the final (steady-state) air velocity in the occupied zone,

$$u_r = K u_o \sqrt{h/L}$$

where K depends on the inlet geometry and Reynolds number.

Further, linear acceleration of the air mass is assumed and the constant, $c < 1$, accounts for the fact that the air in the center circulates at lower speed. The air mass m accelerates as (Newton's law)

$$c\, m \frac{du}{dt} = \dot{m}\, u_o = \text{jet momentum}$$

If n expresses air changes per hour (ach) and if a time constant τ is defined by

$$\frac{u_r}{\tau} = \frac{du}{dt}$$

The time scale for the acceleration of the room air by jet entrainment becomes

$$\tau = 3600 \, cK \frac{1}{n} \sqrt{h/L}$$

Thus, in a room with L = 4 m and a jet inlet diameter h = 0.2 m at an air change rate of 6 per hour, the time constant is roughly 134 s when cK is of order unity.

What does this mean? - When we are interested in the air flow pattern in an office building as it exists during the early afternoon, i.e., some average flow field over an hour or two, we do not care about the transient response of the room air caused by a sudden change of jet momentum. On the other hand, we also neglect the slow drifting of certain temperatures resulting from the effect of the day-night temperature variation on the building thermal inertia.

Thus a first conclusion with regard to simulation of flows under conditions which are unsteady in reality could be formulated as:

> If we want to predict, in a generally unsteady situation, a phenomenon that has a characteristic duration sufficiently above the next lower and below the next higher natural time scale of the overall physical problem, then a **steady-state** simulation is adequate.

This paper will review a few different time scales applicable to air flow in buildings in the next section. A further section is devoted to the rate of growth of one-dimensional natural convection boundary layers on vertical surfaces. Then trends for time-dependent air flow simulation are discussed along with a critical overview of the IEA Annex 20 objectives and an appraisal of its intended impact on the future development of flow field prediction. Annex 20 is entitled "Air flow patterns within buildings" and deals with simulation techniques for single- and multi-zone air and contaminant flow.

2. PHYSICAL TIME SCALES IN BUILDING AIR FLOW

Time scales can only be estimated after the physics of the problem have been analyzed and the relevant mechanisms identified. Often, time constants are very sensitive to geometric dimensions and proportions. This becomes apparent in the following example of the heating of the room-air by a radiator.

The air in a cubical room of length L has an initial temperature of T_0. This air is uniformly heated by a radiator with an effective surface of h^2 and a temperature $T_1 = T_0 + \Delta T$. It is assumed that the convective heat transfer coefficient, u, is constant.

The heat balance for the room air (with temperature T) yields:

$$c_p m \frac{dT}{dt} = u(T_1 - T)\, h^2$$

The time constant τ is defined by the initial rate of heating

$$\frac{\Delta T}{\tau} = \frac{dT}{dt}(t=0)$$

And the time scale for convective heating (of the air) becomes

$$\tau = \frac{c_p\, \rho\, L}{u} \left[\frac{L}{h}\right]^2$$

and is independent of ΔT.

If an entire wall is heated, $h = L$, and for $L = 4$ m, $u = 5$ W/m^{2}K, $\rho = 1.2$ kg/m^3, and $c_p = 1000$ J/kg K, this thermal time scale is $\tau = 960$ s, or about one quarter of an hour. Of course, if the radiator does not cover a full wall, this time constant becomes much larger and grows with the second power of L/h.

The non-dimensional combinations in τ, above, also could have been obtained by dimensional analysis, but not the power of (L/h). The convection time scale is more sensitive to (L/h) than the air acceleration scale discussed in the introduction.

2.1 Transient air movements

A variety of time scales characterizing **steady** airflow have been identified by Hammond[3]. Also, the "age" of air used to quantify ventilation effectiveness [4] [5] [6] is a time scale defined mainly for stationary flow fields. The present discussion is not concerned with time constants of steady flows.

There is another class of flow situations in which unsteady signals are recorded during experiments, although the velocity field is steady: That is when the concentration field (of a neutrally buoyant tracer) is unsteady in an otherwise steady flow. Recirculating clouds of tracer gas may produce a nearly periodic signal at a fixed location with a frequency of the order of u/L, where u and L are typical air velocities and room dimensions, respectively. A tracer gas step-input results in an aperiodic response.

We will turn our attention to truly time-dependent flows that require time-derivative terms in the governing transport equations. Again, we can distinguish between time-dependent flows with steady and with unsteady boundary conditions.

2.2 Time-dependent flows with stationary boundary conditions

If a circular cylinder of diameter d is placed in a incompressible, uniform flow at velocity u, vortices separate from the cylinder surface at a frequency of about 0.2 u/d. A Karman trail develops in the wake of the obstacle. A blunt body under constant boundary conditions may give rise to an unsteady, periodic flow field if there is a feedback from the potential flow pressure field to the boundary layer separation mechanism.

Will oscillations of this type develop in room air flows? - The engineer doing numerical flow simulations would welcome a clear answer to this question. When he attempts to compute a flow with an inherent unsteadiness by a set of equations without transient terms, he will perhaps never reach a steady-state solution. In the case of the cylinder, the steady solution would be unstable except at very low Reynolds numbers.

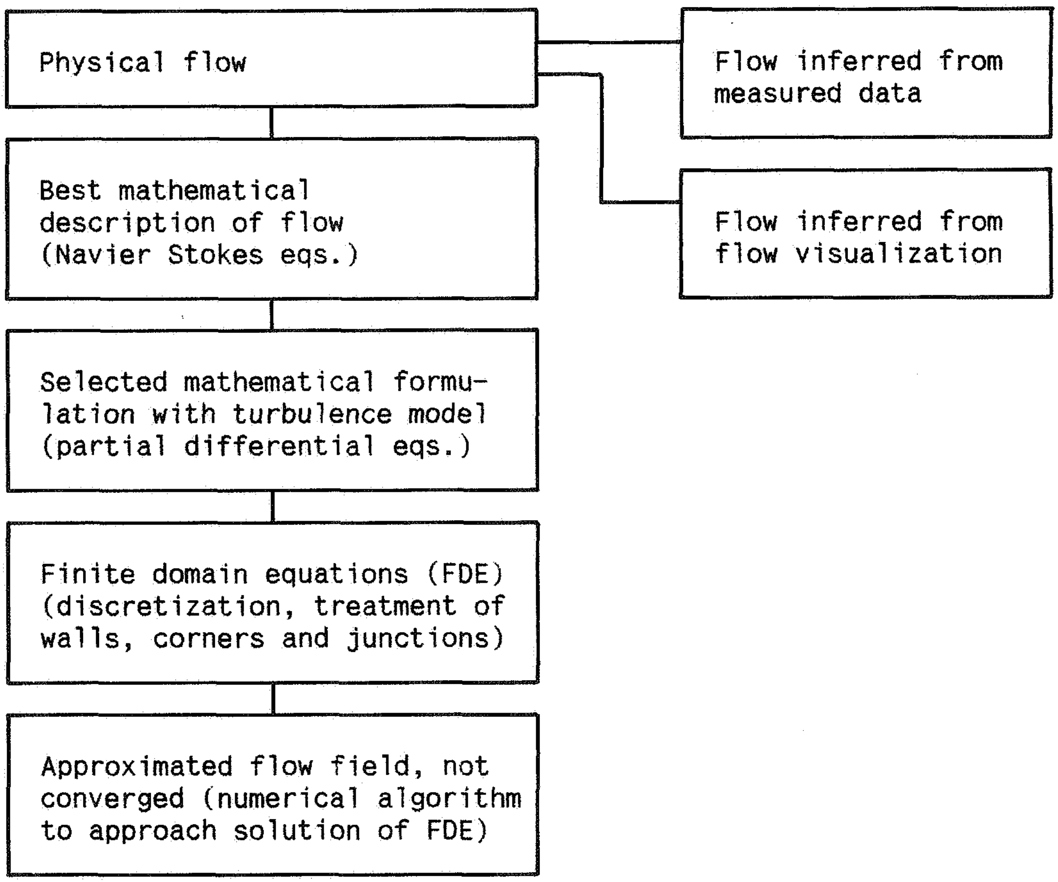

Figure 1 The simulation of flow fields involves a chain of representations where oscillations can develop. Information on the actual physical flow is available only as measured data and through flow visualization.

However, an oscillation during the numerical iteration process does not necessarily point to an unsteady physical flow. And Fig. 1 illustrates that the set of equations for which we seek a solution is merely a highly simplified representation of the actual flow. The source of oscillations can be rooted in the numerical solution algorithm, in the finite domain equations, or in the set of partial differential equations of the model.

Low frequency fluctuations seem to develop sometimes[7] in flows involving natural convection. Since there is an increasing need to simulate such flows, careful studies are needed to learn more about these unsteady phenomena. Parallel tests and calculations by different methods of identical cases, such as conducted by the IEA Annex 20 participants, should shed some light on these problems and help to pinpoint the source and confirm the existence of unsteadiness.

2.3 Time-dependent flows driven by time-dependent boundary conditions

Energy conservation is improved if fresh air is provided only where and when its needed. Demand controlled ventilation systems react to signals from specialized sensors. User-activated control offers the potential of maintaining energy efficiency while improving user satisfaction, because the occupant can adjust the local climate to his individual needs.

Time-dependent air flow predictions are needed to calculate the response of the air flow pattern to such control inputs. With more powerful computers there will be a trend from steady-state calculations to simulation of transient flow fields. Of course, the computation of the dynamic response of a complete air flow pattern requires that static flows are handled routinely and with confidence.

Applications for transient air flow codes:

- Some designs for the house of the future envisage comfort systems in which unoccupied rooms are kept at a temperature and ventilation level far below what is used today (winter situation). When people enter the room, a high-powered system brings the air quality to the required level in a relatively short time. How much power is needed, how much fresh air, and how long does this warm-up take? - These are questions the designer must be equipped to answer.

- A fire starts in a large building. How do hot or toxic gases spread through the building? Can the smoke be removed and escape routes be cleared of toxic gas by the existing ventilation system without feeding the fire with fresh oxygen? These are typical transient problems involving convection of heat and species, buoyancy, and radiation. Some multi-zone smoke control models are reviewed in [8].

- Sudden sunshine through the glazing of an atrium may heat up one of the inside surfaces and cause a drastic change of the internal air flow pattern and temperature distribution. Also a problem for a transient natural convection flow field code.

It is hypothesized that in future ventilation systems the air flow is not just maintained but dynamically "managed" and adjusted to instantaneous needs in the same way as an aircraft is operated and piloted along an optimum trajectory.

When transient simulation codes are applied, a number of different time scales should be considered. Some are shown in Fig. 2 along a logarithmic time axis. These time constants might also be of relevance when the numerical time steps in a transient simulation are selected. Slow processes should allow larger computational time increments.

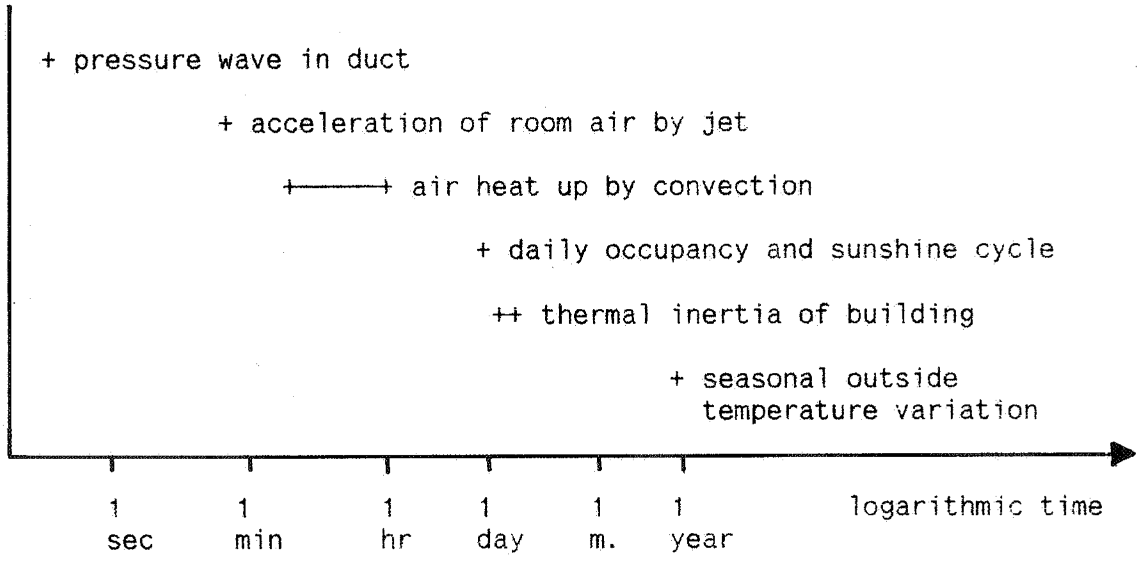

Figure 2 Units of time along a logarithmic scale with approximate ranges of various physical time scales.

In multi-zone air flow in buildings, a number of methods are available today to simulate the transient exchange of air, contaminants, and energy between rooms and with the outside. The intermittent ventilation of a room by opening a window at intervals, for instance, is investigated in subtask 2 of the IEA Annex 20. Initial measurements[9] show that two different time scales are of importance: An initial gravity wave of cold air fills the lower part of the room within the first few minutes after the window is opened, then heat is transferred from the inside walls, and a slow drift of inside air temperature continues for approximately 10 hours depending on the heat capacity of the building structure.

Dynamic simulations of single-room flow fields may also be required to assess the performance of ventilating systems that operate in a pulsed, revolving or intermittent mode. The ability of these systems to mix air masses in a space is discussed in the next section.

3. VENTILATION SYSTEMS THAT GENERATE UNSTEADY FLOW FIELDS

Some novel ventilating systems incorporate schemes for introducing fresh air in a periodic or intermittent[1] way. The technical designs of these systems are not reviewed here, just one aspect of their operation will be discussed: The effectiveness of mixing air in the ventilated room.

A fundamental difference between steady and unsteady flow was demonstrated by J. M. Ottino[10] for applications related to chemical engineering. He has shown experimentally that mixing of different fluids is much more effective in an unsteady flow field than in a stationary flow.

When a blob of ink is introduced in a **steady** flow of a fluid, it will stretch and move and essentially trace a particle path. If the experiment is then reversed with respect to time, the fluid should "unmix" (if molecular diffusion and turbulence are disregarded) and the initial blob should reappear. The convection of a dye in a steady-state flow ideally is a reversible process where errors grow linearly, and the initial state can approximately be recovered.

In a **unsteady** flow the situation is quite different. This is illustrated by the flow visualization recorded by Ottino[10] and sketched in Fig. 3. The unsteady flow between two rotating eccentric cylinders that move periodically in opposite senses effects a thorough mixing of two fluids. Here, the error in reproducing the motion in reverse grows exponentially. Already after a few periods it is practically impossible to undo the mixing.

The experiments suggest that this efficient mixing is accomplished by repeated stretching and folding of fluid filaments, which is typical for unsteady flow with periodic kinematic boundary conditions.

Returning to the ventilating system, we first should decide on the type of ventilation. Is a uniform mixing desired without any pockets of stale air or hot (cold) spots? Or is one-hundred-percent fresh air required near the occupant as in displacement ventilation, where temperature stratification and non-uniform contaminant concentrations are intended? In the latter case, mixing of fresh air with polluted air should certainly be avoided.

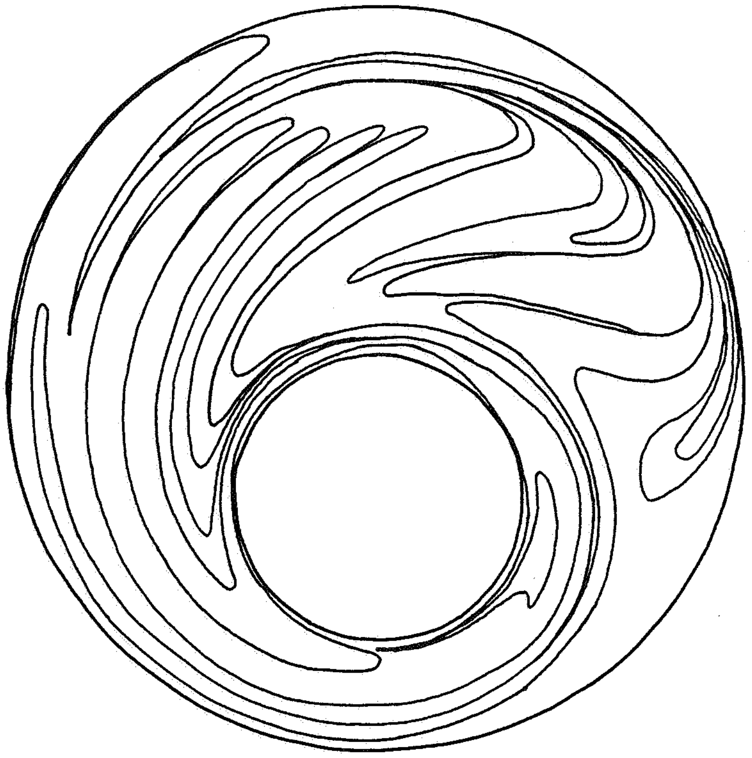

Figure 3 Mixing in unsteady flow: Two eccentric cylinders rotate periodically in opposite directions. The pattern of the mixing liquids after about 10 periods is sketched after a flow visualization photo taken by P. D. Swanson and J-. M. Ottino1).

It can be concluded that intermittent or periodic (i.e., unsteady) ventilation systems should not be employed if mixing of air masses is not desired; however, these systems can be beneficial if high rates of mixing are wanted.

4. GROWTH RATE OF A VERTICAL ONE-DIMENSIONAL LAMINAR NATURAL CONVECTION BOUNDARY LAYER

Correct simulation of free convection on vertical surfaces is of crucial importance in single-room air flow prediction. In an attempt to better understand free convection boundary layers, we have looked for simple analytical solutions. So far we mainly found studies of steady flow along flat plates, where the boundary layer development, as a function of the streamwise distance from the leading edge, is of interest. But the inside walls of rooms start at the floor junction and do not have real leading edges.

Is there a general but simple model for the local behavior of a free convection layer somewhere on a large vertical surface? - Not for steady flow, where the shear layer develops along a streamwise distance. But the velocity and temperature profiles that develop somewhere on a wall in an **unsteady** situation, e.g., after a sudden change of surface temperature, can locally be determined.

It is this transient buildup of a boundary layer that we studied in order to find its relevant time scales. The solution process of numerical simulation often starts with the room air at rest adjacent to walls of different temperatures. Is it possible to consider the growth of the shear layer as a locally one-dimensional problem? - To find out, we have devised an idealized problem resembling Stokes' first problem[11], where a self-similar laminar shear layer is driven by a moving wall. In the present example, the air is initially at rest and has a uniform temperature T_o. The vertical wall has a constant temperature T_w.

Under the hypothesis of a one-dimensional physical process (direction "y" normal to vertical wall) the governing equations for x-momentum and energy were derived under these assumptions:

- Prandtl's boundary layer approximations
- laminar flow, constant viscosity
- density independent of pressure
- Boussinesq approximation for density/temperature relation
- No frictional or compressive heating

In dimensionless form the equation for vertical momentum is:

$$\frac{\partial u}{\partial t} - \frac{\partial^2 u}{\partial y^2} = \theta$$

and the energy equation:

$$\frac{\partial \theta}{\partial t} - \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} = 0$$

With the initial conditions

$u = 0$ $\quad\theta = 0\quad$ at $\quad t = 0$ and $y > 0$

and boundary conditions

$u = 0$ $\quad\theta = 1\quad$ at $\quad t > 0$ and $y = 0$

$u \rightarrow 0$ $\quad\theta \rightarrow 0\quad$ as $y \rightarrow \infty$

The problem lacks natural length and time scales. The only possible combinations of physical parameters with dimensions [length] and [time] are L and τ, expressed in terms of kinetic viscosity, ν, and gravity, g:

$$L^3 = \nu^2 / g \qquad \text{and} \qquad \tau^3 = \nu / g^2$$

Non-dimensional temperature is defined by $\theta = (T - T_o)/(T_w - T_o)$

The other variables are (with primes on physical quantities):

$$y = y'/L \qquad t = t'/\tau \qquad u = u'\tau/\{L\beta(T_w - T_o)\}$$

The coefficient of thermal expansion, β, is kept constant.

The above system is relatively simple and can be solved analytically. However, the author is not aware of a solution in this context. In contrast to Stokes' problem, this system does not have a self-similar solution. The energy equation can be integrated directly because it is free of the other dependent variable, $u(y,t)$. The temperature development alone can be expressed in similarity form and is identical to the solution of related heat conduction problems:

$$\theta = \mathrm{erfc}(0.5\ y \sqrt{Pr/t}\ )$$

The momentum equation is driven by the temperature term (buoyancy). Its solution, therefore, also depends on the Prandtl number and is a function of both independent variables:

$$u = f(Pr,\ y,\ t)$$

Note that the thermal expansion term, $\beta(T_w - T_o)$, has been incorporated in the definition of u and affects the physical velocity linearly.

This derivation[12] will not be taken any further here. For illustration, a few temperature profiles are shown in Fig. 4 for $Pr = 0.7$ and $\nu = 15E{-}6\ m^2/s$. After 100 seconds, for instance, the air at a distance of 44 mm from the wall is heated to one-half of the total temperature difference $T_w - T_o$.

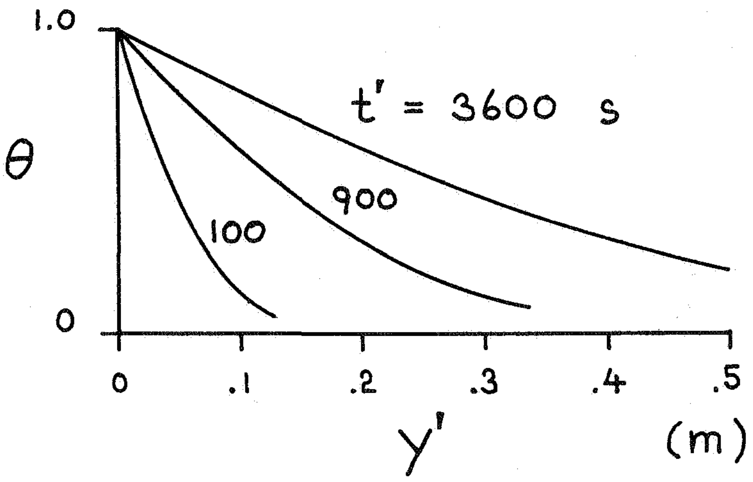

Figure 4 Exact solution for non-dimensional temperature in free convection along hot vertical wall as function of physical normal distance y' [m] and time t' [s] in air.

5. PREDICTION OF STEADY AND TRANSIENT AIR FLOW PATTERNS IN ANNEX 20

The IEA research program on "Energy Conservation in Buildings and Community Systems" sponsors a number of projects (Annexes) that aim at reducing energy consumption of buildings by optimizing the air flow and ventilation systems. The newest air flow project is the Annex 20, "**Air Flow Patterns within Buildings.**"

The task-sharing Annex 20 started in May 1988 for a period of 3 1/2 years. Its main objective is to evaluate the performance of single- and multi-zone air and contaminant flow simulation techniques and to establish their viability as design tools.

The **subtask-1** researchers evaluate flow field simulation programs for the prediction of velocity, turbulence, temperature, and concentration distributions in spaces. Numerical exercises are carried out for clearly defined test cases and the results compared with measurements obtained in identical test chambers by different participating countries.

Five typical test cases have been selected for this study:

b) Forced convection, isothermal flow with wall diffuser,
c) mixed convection, warm-air heating,
d) free convection with radiator and cold window inner surface,
e) mixed convection, summer cooling, warm window surface, and
f) forced convection, isothermal, as in b), with contaminants.

In **subtask** 2, the air, energy, and contaminant flow between rooms and infiltration from the outside are investigated. New algorithms are being developed and evaluated for:

- Flow through large openings
- Inhabitant behavior
- Air flow driven contaminants
- Multi-room ventilation efficiency

Mathematical descriptions of these models will be produced. But the actual implementation in a computerized multi-zone infiltration model is not within the scope of this annex.

The new algorithms will be experimentally verified, and some advanced measurement techniques will be necessary. Improved methods for

- multi-zone airflow measurements and
- enhanced leakage measurements

are developed for that purpose and documented. Validation data sets and physical parameter data bases will be made available on a data bank for later use.

5.1. Need for unsteady simulation

In the near future, design methods will routinely employ infiltration models and flow field prediction tools, and powerful computers will be available in the consultant's office at reasonable cost. Complex flow field simulation codes will calculate the air flow pattern in concert halls, but simplified methods could be more efficient to predict the flow in an office. No doubt, time-dependent flows must also be mastered with confidence.

Today, the researchers participating in Annex 20 strive to advance the state of the art in **steady-state** flow prediction. Engineers of many countries cooperate to learn how to apply modern computational fluid dynamics to building air flow. They share ideas on measurement techniques and, together, interpret experimental and numerical results.

The Annex-20 experts decided early to concentrate on **steady-state** air flow patterns (with a few exceptions in subtask-2 algorithms). As illustrated in Fig. 5, complex flow field simulation is scrutinized under static conditions only, i.e., in the shaded space-coordinate plane of the figure.

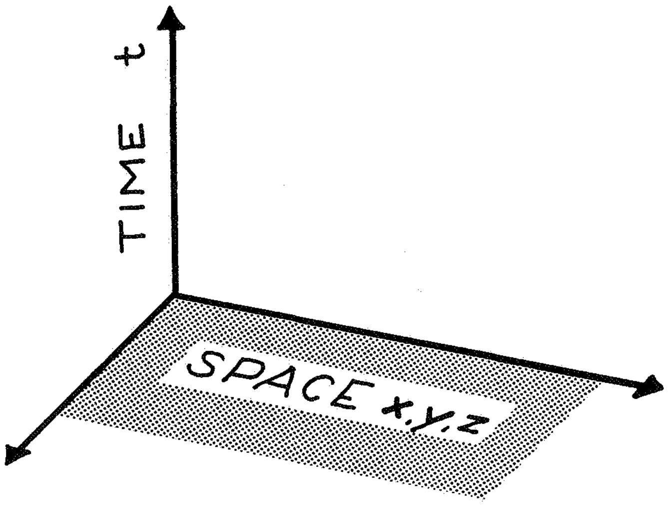

Figure 5 Space and time: Annex 20 aims at preparing a solid basis in the domain of **steady** air flow simulation, as indicated by the shaded "space"-plane.

New ventilation designs and control strategies make future **dynamical** simulation expertise mandatory. The trend toward transient prediction is clear, and the development of new methods will perhaps build on Annex-20 experience.

6. CONCLUSIONS

The goals of the "Air Flow Pattern" Annex are formulated in anticipation of future trends in air infiltration and ventilation. A solid groundwork in numerical and experimental techniques for steady-state building aerodynamics shall be provided. New methods for transient airflow can later be based on this foundation.

A summary of conclusions follows:

- Steady-state simulation is often less expensive and may be adequate for flows that undergo changes of large time scale compared to the observation period of interest. Also, transient behavior with time scales much shorter than this period may be neglected.

- Time scales are sensitive to geometric dimensions and proportions.

- Unsteadiness is observed in different situations:
  - when the concentration of a tracer varies along streamlines of a steady flow field (clouds of tracer gas),
  - periodic shifting of separation points under stationary boundary conditions (Karman vortex trail),
  - oscillations in un-converged numerical solutions, sometimes resulting from problems with the solution algorithm,
  - low-frequency fluctuations in real flows with natural convection or thermal plumes, and
  - fully time-dependent flows with unsteady boundary conditions.

- Low-frequency fluctuations, as observed in experiments with thermal flows, should be carefully investigated.

- Competence in accurate prediction of transient flow fields is required for air flow management in advanced ventilation control systems, in smoke control, or in large spaces with changing thermal loads (atria, lecture theaters).

- Two fluids mix better in unsteady flow. If no mixing is desired, as in displacement ventilation, fresh air should be supplied at constant rate.

- The growth of a one-dimensional laminar free convection boundary layer can be estimated by an analytical formula.

ACKNOWLEDGMENTS

This work was supported by the Swiss Federal Office of Energy (BEW).

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