AIR MOVEMENT & VENTILATION CONTROL WITHIN BUILDINGS

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PAPER 1

THE MESSAGE OF ANNEX 20:
AIR FLOW PATTERNS WITHIN BUILDINGS

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SYNOPSIS

The International Energy Agency (IEA) task-sharing project "Air Flow Patterns within Buildings" was initiated in May 1988 for a duration of 3 $^1/_2$ years. Twelve nations contribute work and expertise and "share the task" specified in the project's objectives. This project and the AIVC belong to the same Implementing Agreement: The Energy Conservation in Buildings and Community Systems Program. As "Attachments" to the Implementing Agreement, they are called Annexes.

The general objective of the Annex is to evaluate the performance of single- and multi-zone air and contaminant flow simulation techniques and to establish their viability as design tools. To reach this goal, the work was divided into two parallel subtasks: One on single-room air and contaminant flow, the other on multi-zone air and contaminant flow and measurement techniques.

This survey paper reviews project objectives and approach, both technically and from the point of view of project management. It offers an overview of the work performed and solutions contributed by the participating countries, it discusses problems encountered during the project and how these were solved, and summarizes final results. It shows how the various technical Annex-20 contributions to this conference are related to the overall Annex effort. General conclusions are drawn, consequences for future international projects are examined, and the main message of the multi-national program is formulated.

1. Introduction

"It should become possible to predict air flow patterns within buildings by numerical simulation!"

\- This was concluded by a small group of ventilation experts who met in September 1987 in Ittingen, Switzerland. New commercial codes appeared on the market, and research codes were developed at universities and research labs. The workshop participants expected that some expensive laboratory tests could be avoided if air flows in rooms, infiltration between rooms, and exchange with the outside atmosphere could numerically be predicted with a certain degree of confidence. New tools would enable the designer to evaluate different variations of a ventilation concept on a computer. Contaminant transport within buildings or rooms could be modelled and the effectiveness of ventilation assessed in a systematic way.

The idea to start a new "IEA Energy Conservation in Buildings and Community Systems" Annex was born: Many promising simulation models existed and specialists have started to apply them to real buildings [1]. Experienced engineers voiced skepticism, while their younger colleagues looked for the "best" computer programs! It was the right time to survey and evaluate existing methods on an international basis.

Annex 20, *Air Flow Patterns within Buildings*, provided the framework to bring the experts together, to compile information, and to undertake validation exercises. For single- and multi-zone air flow, experimental data sets were required as benchmark cases. Therefore, experiments had to be specified for the project. Soon the scope of the Annex was extended to include the evaluation and documentation of advanced measurement techniques for multi-zone air flow and the development of new algorithms to model special flow mechanisms.

During the past three years, Annex-20 workers have learned quite a lot about air flow simulation. They will present some of their results at this conference, and the knowledge will be made widely available through publications and references in the AIVC bibliographic data bank "AIRBASE".

We have learned how to calculate air movement in buildings and rooms but also encountered and identified problems and found ways to deal with these. The experienced user of air flow codes will appreciate the benefits of numerical simulation:

- Information is available in all points of the flow field (on computational grid).
- Any desired variable of the physical model can be output and plotted: Air velocity and its fluctuations (turbulence), temperature, concentrations of contaminants and humidity, "local age" (an indicator of the "freshness" of the air), and comfort parameters (thermal comfort and "risk of draft"). Also heat transfer to and from window and radiator surfaces.
- Sensitivity tests and parameter variations are easy to do, and computed trends should be even more reliable than absolute values of variables.

The objective of the Annex is expressed in one short sentence (see next section), but its relevance was immediately recognized by all countries of this IEA Implementing Agreement. Thirteen nations decided to participate in Annex 20 (Section 3).

One reason for this wide participation certainly was the strong impact the work has on energy conservation. The trend to air-tight buildings with improved thermal insulation asks for controlled air exchange as already documented by the work of Annex 18, *Demand Controlled Ventilating Systems*, Annex 14, *Condensation*, and Annex 9, *Minimum Ventilation Rates*. The energy required to exchange the air grows with the temperature difference between fresh outside air and supply air to the rooms. In mechanical Systems, a substantial portion of the energy is used to move the air through the ducting and the rest for cooling or heating and other conditioning. The former is a function of the air change rate, the latter of temperatures and heat recovery, if installed.

This energy consumption is of growing significance in relation to the heat loss through the envelope of well insulated buildings. The designer of these new-generation buildings wants to know how the air flows before the house is built!

2. Annex 20 objectives

Formal participation in this task-sharing Annex is based on the legal text [2] that defines project objectives, tasks, and responsibilities. The document states:

> "Research attention has recently been given to the patterns of air circulation within rooms and through buildings, to ensure that fresh air supply and pollutant removal requirements are effectively obtained without undue use of energy resources.
>
> "Recent developments in measurement techniques and computer hardware open new possibilities to study this phenomenon, while several advanced computer-based simulation methods have been produced in an attempt to describe this flow.
>
> "The objectives of this task are to evaluate the performance of single- and multi-zone air and contaminant flow simulation techniques and to establish their viability as design tools. The task is divided into two subtasks:
>
> (a) Subtask 1 - Room air and contaminant flow;
> (b) Subtask 2 - Multi-zone air and contaminant flow, including related measurement techniques."

3. General approach and project organization

Once the main objectives were formulated [2], we had to find the most effective approach to reach them. At the "Kick-off" meeting in May 1988 we decided on the organization and structure of the project.

We tried to keep it as simple as possible and agreed on the following:

(1) Two parallel subtasks for the full project term, because the methods are different for single- and multi-zone air movement.

(2) Each subtask has a subtask leader responsible for the scientific product of the task.

(3) The technical work within each subtask is structured in *Research Items* (RI), each with a RI-*Description* (RID). The RID states objectives, methods, completion date, and the principal investigator (PI).

(4) The project has a preparation phase, main performance, and reporting phases. Observer status is restricted to the preparation phase.

(5) Expert meetings are held twice a year (8 total).

The recommendations in the guidelines [3] of the IEA Energy Conservation in Buildings and Community Systems (ECB) Implementing Agreement have been observed.

Wide publicity for our work was sought by the publication of a news letter and by inviting interested persons of participating countries, - in addition to the active experts, - to the Annex meetings. Early dissemination of information (within Annex-20 countries) was promoted.

As a general policy, the experts were encouraged to publish their own work already during the course of the project as Annex reports, in journals, or at conferences. Reports and publications were advertised in a "List of Annex-Documentation," that was updated periodically. It now holds over 100 titles and abstracts. Records of final publications are also fed into AIRBASE.

This policy also led more than twenty Annex experts to report their own work directly at this AIVC Conference.

Table 1 lists the participating countries along with their subtask commitments and cities where they organized meetings.

Country	Commitment: Subtask 1	2	Expert Meeting: City and date	
Belgium		full	Lommel	Nov. 89
Canada	full	c	Ottawa	Sep. 91
Denmark	full		Aalborg	May 89
Finland	full			
France	full	full	Nice	Oct. 90
Germany	full		Aachen	Apr. 91
Italy	full			
Netherlands	full STL	full	Lommel	Nov. 89
Norway (to April 90)	full		Oslo	June 90
Sweden	full	c		
Switzerland	full	full STL	Winterthur	May 88
United Kingdom	c	full	Warwick	Nov. 88
USA	c	full		
totals 13	10	6	8	

Table 1 Participating countries and meeting sites. The meeting in Lommel, Belgium, was organized jointly by Belgium and the Netherlands. (**full** = full commitment, **c** = contribution, **STL** = subtask leader)

We have cooperated with other ongoing projects: Annex 5 (AIVC), Annex 23 (and COMIS [4]), and the IEA Solar Heating and Cooling Task XII, *Building Energy Analysis and Design Tools for Solar Applications*.

4. Subtask 1: Room Air and Contaminant Flow

Objectives for this subtask are:

- To evaluate the performance of three-dimensional complex and simplified air flow models in predicting flow patterns, energy transport, and indoor air quality,
- to show how to improve air flow models,
- to evaluate applicability as design tools,
- to produce guidelines for selection and use of models,
- to acquire experimental data for evaluation of models.

4.1 Approach

The basic approach was to solve *identical problems* in different participating countries by *different methods* and in different facilities. The results are now collected, analyzed, and compared [5]. This approach not only allows each country to assess the performance of the employed method but will also provide a methodology and experimental data sets to evaluate simulation models of the future.

Special problems encountered during this evaluation process were studied in separate research items: Modifications of turbulence models for low Reynolds numbers and thermal buoyancy [6], [7], [8], simulation of air supply devices [9], [10], or the specification of temperature boundary conditions that account for radiation.

Simplified methods have also been evaluated, and in some cases even developed [11]. These have a particular appeal to the design engineer, because he can apply them with little expenses for resources and specialized training.

Complex and simplified simulation methods have been evaluated by applying them to four different benchmark cases [5], each representative of a particular basic air flow phenomenon, such as forced or natural convection. Measurements and simulations have been carried out simultaneously by different groups. To compare the *numerical* performance of simulation methods, simple two-dimensional flow fields have also been calculated.

Available codes for air flow simulation are listed in [12]. Some general air flow codes used in North America and elsewhere may be found in [13]. And a critical review of computational fluid dynamics procedures was prepared for the ASHRAE by Baker and Kelso [14].

Table 2 shows a partial list of air flow programs. The programs that were used by Annex-20 participants are indicated by country names. "FloVENT" (distributed by FLOMERICS Ltd., UK) is used by IEA Solar Task XII, Project A.3, *Atrium Model Development*. All programs listed use finite-volume discretization (sometimes called finite-difference or finite-domain) with the exception of three, which employ the finite element method (FE). Subtask-1 workers have used eight of the listed algorithms. Denmark has its own research code.

Name	Origin of Code	Type	Annex-20 users	Remarks
ARIA	Abacus, UK	C		
ASTEC	Harwell UK	C		
CALC-BFC	Chalmers S	R	Sweden	own develop.
CHAMPION	TUD NL	R		
EOL-3D	INRS F	R	France	
EXACT3	NIST USA	R	Canada	
FEAT	UK	?		FE
FIDAP	FDI USA	C		FE
FIRE	AVL A	C		
FLOTRAN	Compuflow	C		FE
FloVENT	FLOMERICS UK	C		SHC Task 12
FLOW-3D	Harwell UK	C		
FLUENT	Creare USA	C	Germany	
JASMINE	BRE-FRS UK	R		fire, smoke
KAMELEON	SINTEF N	R	Norway	
PHOENICS	CHAM UK	C	Switzerland	
SIMULAR AIR	AVL A	C	Germany	
STAR-CD	CD UK	C		
TEMPEST	Battelle USA	R		
WISH-3D	TNO NL	R	NL, Finland	

Table 2 Computer codes for air flow simulation. Detailed information may be found in [12]. (**R** = Research algorithms, **C** = commercial algorithms, **FE** = finite element method, **SHC** = IEA Solar Heating and Cooling Implementing Agreement)

The Subtask-1 conclusions are restricted to the methods and programs actually used and are not applicable to others.

4.2 Results and contributions to this AIVC Conference

Table 3 shows an overview of papers/posters contributed by subtask-1 experts to this AIVC Conference. Contributions are identified by the name of the first author and session number.

Problem	*Measurement*		*Simulation*	
Air supply device	Ewert	5A	Chen = Ewert Heikkinen Skovgaard	3A 5B 5B
Room flow field - turbulence	Sandberg Zhang	3A 5C		
- concentration	Heiselberg	3A		
- scaling & LRN			Moser Skovgaard	3A 5B
- water scale-model	Biolley	3A	= Biolley	
Simplified methods - zonal model			Inard	3A
- jet models			Nielsen	1
Evaluation	Whittle	1	= Whittle	

Table 3 Papers and posters presented at this 12th AIVC Conference by Annex-20, Subtask-1 investigators: Name of first author only is shown, along with conference session number. ("= **Ewert**" means, the same paper reports measurements *and* simulations, **LRN** = low-Reynolds-number effects)

The table shows that efforts have concentrated on problem areas (air supply) and on detailed measurements of flow quantities that are important to occupant comfort (turbulence intensity and concentrations of contaminants). Two contributions report the development and verification of simplified methods. The Summary Report by Lemaire [15] covers all work performed by subtask 1, whereas conference contributions, table 3, only report highlights.

4.3 Technical problems with numerical simulations

The major problems encountered during numerical simulation may roughly be grouped into five classes:

(1) Turbulence model at existing range of Reynolds numbers and near walls.

(2) Natural and mixed convection at cold or warm surfaces.

(3) Simulation of air supply device.

(4) Problems with number and size of numerical control volumes (computational grid) and difficulty to reach grid independent solutions.

(5) Numerical procedure to reach solution of system of finite difference equations.

Attempts have been made to handle these problems, as documented in several Annex-20 technical reports. But many approaches still leave plenty of space for improvement, and future research into these areas is badly needed.

Problem (1): We have not tested turbulence models other than the widely-used k-epsilon closure [12]. But experts have agreed that so-called low-Reynolds-number corrections are needed near walls and at low turbulence levels [7].

Problem (2): Three methods of dealing with heat transfer had been tried. The desirable approach is to prescribe wall temperature and have the program compute the heat flux. This works for forced convection (with wall functions) but is difficult for free convection because it requires a fine grid near the surface, low-Reynolds-number corrections in all equations, and careful setting of boundary conditions for computed variables. More work needs to be done on this method.

The second approach is to prescribe wall temperature and an empirical local heat transfer coefficient. This approach works well for window or radiator surfaces.

The third method is to estimate the local heat flux by empirical formulas and apply it in the simulation as a heat source (or sink) over the surface. If the correct heat flux (in W/m^2) is available, the method is reliable and does not require very fine grid, but the surface temperature is not automatically calculated.

Problem (3): A number of approaches are reported at this conference (table 3). It would be helpful if the manufacturers of air diffusers would publish some near field data (e.g., profiles in front of the device) with their technical specifications.

Problem (4): All computations were done with cartesian grids, where grid lines run through the entire flow domain ("tensor grid"). This mesh system has the disadvantage that grid refinements, also, extend from wall to wall, and into regions, where a fine resolution is not needed and cells with undesirable large aspect ratios may appear. Computational meshes with local grid refinement [12] were not tested. We found that grid independence was not reached.

Problem (5): Convergence of computations of flow fields with buoyancy effects in general is slow or inexistent. Monitoring of convergence is assisted by plotting the logarithmic residuals against iteration number (sweep number). Adjustments of relaxation factors during the solution process is normally required.

Experimental and numerical results suggest unsteady air motion under certain conditions at high Rayleigh number. However, this must still be verified. If, in fact, steady solutions do not exist under some circumstances, time-dependent simulation would be appropriate.

Simulations of case **e** (mixed convection, summer cooling) have shown asymmetric flow fields at symmetric boundary conditions and geometry. Two stable solutions (with the jet turning left or right, respectively) and one unstable but symmetric solution were observed. The latter is obtained by just computing one half of the flow field and enforcing symmetry-plane conditions. The asymmetric flow pattern is confirmed by measurements [16].

5. Conclusions from Subtask-1 evaluation of simulation methods

A detailed description of the benchmark exercises and quantitative comparisons of measurements and simulations with a critical evaluation is presented by Whittle [5].

What can we say now about the performance of room air flow simulation techniques and about their applicability as design tools? - It is certainly not our intention to say which computer code is the best!

It is not a question of codes but of *methods* for flow simulation. The available computer codes are only one component of a method. Figure 1 shows a few components or *techniques* that make up a method.

Simulation Method consists of:	Remarks/Examples:
Turbulence model	k-ε two-equation model
Computational grid	non-uniform grid with 30x30x30 cells, finer near walls
Boundary conditions	for velocity and turbulence at supply device for temperature or heat flux at surfaces for concentrations at contaminant sources etc.
Wall functions	appropriate for forced or free convection
Difference scheme	upwind, hybrid, PL, QUICK, etc.
relaxation technique	techniques to accelerate convergence
Computer code	(see table 2 for examples)

Fig. 1 A simulation *method* has many components, seven are shown here. (**PL** = power law, **QUICK** = quadratic upstream interpolation for convective kinematics [17])

Most commercial and some research codes include options to select or influence the features listed in figure 1.

The "best" method then would be the one that combines the "best" techniques. The evaluation [5] and summary [15] reports contain specific discussions of each technique.

The simplified methods must also be included in a general evaluation, of course. To assess performance and viability of methods, performance *criteria* should first be specified. But each potential user has different requirements. Three groups of users are listed in figure 2.

Users of simulation methods

	Remarks:
Designers and consultants	1) computing themselves 2) subcontracting air flow simulations
Specialists of a CFD service-organisation	
Scientists and students at research labs	

Fig. 2 Potential users of simulation methods. (**CFD** = computational fluid dynamics)

The engineers who design ventilation will either use the simulation methods themselves or they commission the CFD analysis to an external service. Sometimes, they do an in-house simulation and back it up by a parallel external verification.

The use of advanced flow simulation techniques requires specialized skills. Therefore, private or public service groups are getting established in different countries. These organizations ideally have specialized staff and the right hard- and software to do useful flow field analyses within reasonable cost and time.

The third group are researchers at universities, research institutes, or industrial laboratories. These users spend considerable time with simulation algorithms with the following objectives:

- To develop or improve computer codes,
- to validate CFD-models with experimental data,
- to validate (and calibrate) simplified methods by comparison with CFD-models,
- to document methods, to train new users, and to transfer knowledge to the engineering community.

Each of the three groups of figure 2 has different criteria as illustrated in figure 3.

User: / Criterion:	Design	CFD Service	Research
Cost of resources: staff, training, hard- & software	important		
Cost per case: labor, CPU-time	important		
Speed: response time	crucial	important	
Reliability & expediency: accuracy, detail, questions answered?	important	crucial	crucial
User-friendliness: ease of input, presentation of results	important	important	important
Interaction with other programs: building dynamics, radiation, CAD, etc.	important	important	

Fig.3 Criteria for performance of simulation methods by different user groups. (**CPU** = central processor unit, refers to machine-time and fee for using computer, **CAD** = computer aided design)

The entries in the table of figure 3 reflect the author's opinion as based on discussions during Annex-20 expert meetings. The weight "crucial" means that this user would *not* undertake a numerical simulation if that criterion were not met. The CFD-service has essentially the same criteria as the designer but is in a better position to optimize cost. For instance, the CFD-service can more efficiently maintain a skilled staff.

"Response time" refers to the span of time elapsed between formulation of task and delivery of usable results. "Expediency" expresses whether the computed output answers the questions of the user or client. For instance, have velocities, temperatures, and concentrations been calculated and output for the zones of interest, have local comfort and indoor air quality parameters been determined?

A novel approach to make detailed CFD calculations available in the design office was developed by Chen [18], [19]: He has pre-calculated a large number of typical flow patterns with a CFD code and arranged them in a systematic manner in a catalog called "Air Flow Pattern Atlas." So far, office rooms with different dimensions, loads, and ventilation systems have been modelled. The publication of this part of the Atlas is in preparation. Engineers may consult the Atlas to get a quick idea of air motion, indoor air quality, and draft risk (comfort parameter expressing the human sensation of air current) in a situation that resembles an actual design.

5.1 Technical conclusions

The work of Subtask 1 [15] and the evaluation of benchmark exercises [5] lead to these conclusions:

- CFD-simulations are useful when values of difficult-to-measure variables are needed in all points of the flow field.
- CFD-simulations are useful to study the sensitivity of flow patterns to small changes of conditions (trends).
- CFD-simulations are useful to predict air flow patterns for critical projects, i.e., when neither similar experience nor measured data exist (large spaces, unconventional ventilating systems, strong buoyancy effects).
- Simplified methods are useful to estimate the throw of supply air jet, the maximum velocity in the occupied zone, or the thermal plume in a radiator-window configuration.
- The catalog of pre-calculated cases (Atlas) is useful to get a quick overview of flow patterns that may develop in standard office rooms under various conditions.

In his evaluation report [5], Whittle concludes that CFD codes can predict room air movement with sufficient realism to be of use to design practice. Skill and experience are still required to use these codes. Many problems have been identified during this project, and Whittle [5] mentions three areas where further work is needed (modelling of supply jet, modelling of turbulence, thermal wall functions).

The Subtask-1 work demonstrates that CFD methods and several simplified approaches are now ready to be used as design tools. These powerful techniques, familiar to aerospace, propulsion, and environmental engineers, are still relatively new to building applications. Initial use will be by specialists, but further developments of methods and improvements of the user-interface will lead to a wide acceptance in the not-so-far future.

6. Subtask 2: Multi-zone air and contaminant flow and measurement techniques

Objectives for this subtask are:

- To develop new algorithms for specific problems, as flow through large openings, inhabitant behavior, air-flow-driven contaminants, or multi-room ventilation efficiency,
- to develop new, or improve existing measurement techniques,
- to collect and test input data sets of experimental data (reference cases for code validation),
- to establish a data base of physical parameters for multi-zone modelling in the design process.

6.1 Approach

The goals of this subtask point in two different directions:

- preparations for new multi-zone simulation packages,
- publication of a state-of-the-art measurement techniques handbook.

The subtask experts have developed algorithms for new multi-zone air flow models but have not engaged in developing such programs. The actual development may later be undertaken by individual countries and is also underway in IEA ECB Annex 23, *Multi-zone air flow modelling* [4]. The data bases will be indispensable for validation of these simulation tools.

To acquire the data for the data sets and to verify the algorithms for the planned simulation packages, proven measurement techniques have to be available. The authors of the measurement techniques guide have emphasized that measuring a particular flow parameter involves more than just 'putting in a sensor':

- Clear understanding of the *physics* of the investigated flow (e.g., effects of variable density on volumetric infiltration measurements),

- Clear understanding of the *purpose* of the measurements (e.g., if concentrations are measured to determine "local age of air," the definition and significance of this air quality indicator must be known),

- Selection of *equipment* and sensors and their characteristics,

- *planning* and setting up of experiments in a cost-effective way (e.g., number and locations of measured points should be optimized to get meaningful results in reasonable time),

- Data acquisition, *interpretation*, and presentation,

- *error analysis*, and problems that may be encountered.

The approach in the subtask included a state-of-the-art review of techniques and know-how relevant to the above goals. It turned out that many participants had experience in one or the other of the special fields. The team managed in a perfect way to bring this competence together. Topics to be addressed in depth have been assigned to six task groups, each with a responsible coordinator:

New algorithms:
2.1 Flow through large openings and single-sided ventilation [20],
2.2 Inhabitant behavior, e.g., simulated use of doors and windows [21],
2.5 Air-flow-driven contaminants [22],
2.6 Multi-room ventilation efficiency and ventilation performance index [23].

Measurement methods:
- 2.7 Multi-zone air flow measurement methods and techniques to measure ventilation efficiency [24].

Data bases and data sets:
- 2.11 Data bases for planning and validation [25].

The work of these groups is reported in the referenced Annex reports and in several technical reports.

6.2 Results and contributions to this AIVC Conference

Table 4 shows an overview of papers/posters contributed by subtask-2 experts to this AIVC Conference. Contributions are identified by the name of the first author and session number.

Problem *RI*	*Experiment*	*Modelling*
2.1 Large openings - algorithms - single-sided ventilation: effects of wind and wind turbulence	 Bienfait 1	 Pelletret 1 = Bienfait Rao 1
2.2 Inhabitant behavior		Roulet 3A
2.5 Air-flow-driven contaminants - sources - moisture	Phaff 1 Gehrig 3A	= Phaff Jiang 3A
2.6 Multi-room ventilation efficiency		Haghighat 3A
2.7 Measurement techniques	Roulet 3A	

Table 4 Papers and posters presented at this 12th AIVC Conference by Annex-20, Subtask-2 investigators: Name of first author only is shown, along with conference session number. ("**= Phaff**" means, the same paper reports experiments *and* models, **RI** = Research Item number).

The papers listed on the first line of each research item contain an overview of the work of that task group, whereas the remaining contributions report specific results. Full documentation of the work is contained in the Annex reports referenced in section 6.1 above.

6.3 Technical problems with multi-zone modelling

Instead of listing all the problems that had to be solved, one exciting discovery is mentioned here to illustrate the type of questions that were discussed in this subtask.

French researchers made measurements on an experimental house with an opening exposed to turbulent wind [26]. Haghighat et al. [27] have made similar investigations. Both groups found that the air exchange rate through the opening depends on the turbulence intensity of a head-on wind.

It was speculated that air compressibility comes into play. It was argued by some, that compressibility will have vanishing effects at these low velocities (low Mach numbers), by others, that a repeatable experimental result cannot be lightly ignored.

An order-of-magnitude estimate shows for a turbulent wind velocity, $w = W + w'$ (where W is the mean velocity):

Pressure fluctuation: $$\delta p \approx \delta\{ \rho/2 \ (W + w')^2 \}$$

$$\delta p \approx \delta\{ \rho \ W \ w'\}$$

The *amplitude* of the fluctuation (in *italics*) is approximately

$$dp \approx \rho \ W \ w'$$

and w'/W expresses the turbulent intensity of the wind.

How much does this small pressure difference compress a fixed mass, m, of air? The volume, V, initially occupied by this mass is $V = m / \rho$.

The relative change of volume is $dV/V = - d\rho/\rho$. The air density in the room reacts to the applied pressure, *dp*, in a adiabatic manner [27], and

$$dV/V = - d\rho/\rho = - (\partial\rho/\partial p)_{is}\, dp/\rho \approx \pm W\, w'/ a^2 ,$$

where the isentropic (is) pressure-dependence has been expressed by the speed of sound, a. Thus, the rough estimate yields:

$$dV / V \approx (W/a)^2 (w'/W),$$

i.e., the relative volume change is proportional to the square of the wind Mach-number multiplied by the turbulence intensity. Example: At W = 10 m/s the Mach number is, W/a = 0.03 ; at 20 % turbulence the volume change becomes 0.0002, or 40 liters for a house of 200 m^3. If this displacement of air is renewed periodically, the exchange rate (liter/s) would be *displacement* x *frequency*.

It is interesting to see that the Mach number appears in an infiltration problem. The subtask-2 team has analyzed and documented many surprising phenomena that have an impact on modelling or diagnostics like this compressibility effect.

7. Conclusions from Subtask-2 work

The accomplishments of this subtask extend over many different areas, and on each sub-project experts have discussed and drawn technical conclusions as reported in [20] - [25].

The main conclusions are:

- *Algorithms* of practical realism and manageable complexity have been developed and tested and are ready for integration into multi-zone air flow models.

- *Measurement techniques* relevant to multi-zone air, contaminant, and energy transport have been critically reviewed, updated to current state of knowledge, and presented in a way comprehensible by users.

- A methodology for compiling *validation data* has been developed and demonstrated by storing two measured data sets of existing buildings in a numerical data base.

- *Improvements* to experimental methods have been tried out, new physical effects discovered, and novel algorithmic methods developed.

8. General conclusions and recommendations for future work

It is no exaggeration if I say that work for this project has been done with great enthusiasm! Air flow pattern pioneers came to the meetings, willing to share their best ideas with international colleagues around the table, - always alert to point out flaws of discussed concepts, and open to fair criticism. The atmosphere of efficient teamwork was a good experience by itself. And the commitment of all participants to the common goals made the project a success. The creativity of many has contributed to the joint product of the Annex. As expressed in one of the news letters, - "Air flow research is people."

8.1 General technical conclusions

- The experimental verification of proposed design methods has shown that *validation* is an impossible task: Experiments are never perfect and *all* potential applications of a method cannot be foreseen. Therefore, the performance of a design tool may only be *evaluated* for certain specific uses. Annex experience shows that independent, parallel experiments should be conducted if possible.

- Attention has been focussed on technical *problems*. In both subtasks, these have been described and analyzed. Future progress is only possible by concentrating on these problems and not by ignoring them.

- The technical results are in a form that can be implemented in practice, as well as in future projects.

8.2 General project conclusions

- On the whole, project objectives have been met within the planned 42 project months. In some research items much more has been done than intended, in others emphasis had shifted a little and working objectives been reformulated. This is a consequence of a dynamic approach, where the direction of a new step is based on previous results. In some instances, the availability of staff and facilities had an influence.

- For Annex 20, it is true that the whole collaborative achievement amounts to *more* than the sum of individual national efforts. That means, the international teamwork produced a synergetic effect. Some results would have been impossible without international cooperation, as for instance, the verification of a theory developed in one country by test data from another.

- Cooperation with the IEA Air Infiltration and Ventilation Center, AIVC, was excellent. The assistance by the Center was vital to the success of Annex 20 (e.g., bibliographic searches, data handling and storing, reviewing reports, publishing, and providing the opportunity of this conference).

- In a task-sharing Annex, as this one, project leaders have no financial incentives to control productivity of participants. In spite of this, all participants have felt responsible and were well motivated to deliver promised work of high quality.

8.3 Recommendations for future work

- At special workshops, Annex-20 participants have developed proposals for new IEA Energy-Conservation-in-Buildings-and-Community-Systems projects. Two of these, *Air Flow in Large Enclosures* and *Residential Ventilation Systems*, are now in review by the Executive Committee. In fact, the products of Annex 20 may directly flow into these two projects and into Annex 23.

- International projects should have immediate impact on conservation of energy and environment. Their results should be in a form easily implemented in engineering practice. On the other hand, such projects are ideally suited to study the physics of energy systems. Therefore, objectives should reflect a sound balance between fundamental *and* applied products.

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