bulletin M83:23

THE NATIONAL SWEDISH INSTITUTE FOR BUILDING RESEARCH

Models of Infiltration and Natural Ventilation

Mats D Lyberg

Förteckning över meddelande/bulletin 1983

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C:a pris 35:– exkl moms. 36 s.

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En granskning av sex rumsliga flödesmetoder avseende pendlingsområden.
Urban Fransson
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M83:19 Lokala tätortssystem. Framväxt – planering – alternativ. Ett beskrivningssystem för yttre fysisk form.
Ann-Mari Eriksson
C:a pris 35:– exkl moms, 78 s.

M83:20 Residens and windows.
1. Shielding of windows.
Mats D Lyberg
C:a pris 25:– exkl moms, 20 s.

M83:21 Residens and windows.
2. Airing.
Mats D Lyberg
C:a pris 25:– exkl moms, 28 s.

M83:22 Noggrannhet i primärnätet. En undersökning av kravens relevans.
J Abrahamsson och Å Lindberg
C:a pris 25:– exkl moms, 26 s.

M83:23 Models of infiltration and natural ventilation.
Mats D Lyberg
C:a pris 30:– exkl moms, 44 s.

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Distribution och försäljning sker direkt från

STATENS INSTITUT FÖR BYGGNADSFORSKNING
Informationsavdelningen
Box 785
801 29 Gävle
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The publication series Meddelande/Bulletin describes current and concluded research projects and some other activities at the National Swedish Institute for Building Research. The respective authors are responsible for the contents. The series began in 1974 and the publications are numbered consecutively every year. Beginning with the bulletins of 1977 copies will be sold at cost. Publications from earlier years will be distributed free of charge as far as supplies permit.

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FOR BUILDING RESEARCH
Information Division
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STATENS INSTITUT
FÖR BYGGNADSFORSKNING

ISBN 91-540-9183-7
ISSN 0347-4348

EXELLAN GRAFISKA
Gävle juni 1983

SAMMANFATTNING

I denna rapport beskrives en undersökning av effektiviteten hos modeller för infiltration och naturlig ventilation i bostadshus. Totalt undersökes åtta olika modeller. Modellparametrarna bestämmas genom en jämförelse med data från sex olika ventilationsundersökningar. Parameterantalet har varierats för varje enskild modell. Effekten av att komplettera modellerna med en faktor som tar hänsyn till vindriktningen har undersökts. Likaså har effekten av att variera storleken av den exponent, som bestämmer hur lufthastigheten beror av tryckskillnaden över en öppning, undersökts.

Resultaten utvisa att de effektivaste modellerna är de där den dimensionslösa luftomsättningen, definierad i denna rapport, ges som en funktion av forhållandet emellan vindkraften och termiska drivkrafter. Resultaten utvisa likaledes att modelleffektiviteten kan förbättras avsevärt om uppgifter om tryckfördelningen över byggnadsytan finns tillgängliga, även om antalet modellparametrar minskas. Om de modeller som här beskrives skulle användas för att förutsäga luftomsättningen, kan man draga slutsatsen att de skulle göra detta med ett medelfel av 10 eller 15 %, förutsatt att värdet på parametrarna är känt.

SUMMARY

In this report the efficiency of models describing the infiltration and natural ventilation in buildings is investigated. Altogether eight different models are considered. The parameters of the models are determined by fit to data from six different ventilation experiments in residential buildings. The number of parameters in each model is varied and the effect of this on the model efficiency is evaluated. The effect of simple corrections of the models for a dependence on the wind direction is considered. The effect of varying the exponent of the pressure difference in the description of the flow rate through an opening is also investigated.

The results show that the most efficient models are those where the dimensionless rate of air exchange, defined in this Report, is given as a function of the ratio of the aeromotive force to the bouyancy force. The results also show that the model efficiency is considerably improved if information on the pressure distribution over the building surface is available, even if the number of free parameters of the model is reduced. If the models were to be used for predictive purposes, the results of the fits indicate that, provided the values of the parameters can be properly chosen, the models would predict the rate of air change with a average error of 10 to 15 %.

CONTENTS

Illustrations: F Glaas

NOTATION

a	model parameter
ACH	air changes per hour
b	model parameter
C_d	discharge factor
C_{pe}	external pressure coefficient = $(p_e-p_o)/(\rho u^2/2)$
C_{pin}	internal pressure coefficient = $(p_{int}-p_o)/(\rho u^2/2)$
Fr	Froude number defined as $u^2 * T/(2*g*h_T*\Delta T)$
g	constant of gravity
h_{min}	lower height of opening
h_{max}	upper height of opening
h_T	thermal height of building (height at which $p=0$ when $u=0$)
I_γ	dimensionless infiltration = $ACH*V*Fr^\gamma(1+\gamma)/(3600h_T Lu)$
L	half of the building circumference
L_i	width of opening
n	number of parameters in a model
N	number of data points in a data set
p_e	wind pressure on building facade
p_{int}	interior (static) pressure of building
p_o	reference (static) pressure in the definition of C_{pe}
S^2	object function to be minimized in a fit
T	average indoor- outdoor air temperature
u	reference wind velocity
z	height above ground
α	model parameter describing leakage area
β	model parameter describing size of window
γ	exponent of variable p in description of flow rate
ΔC_p	$\Delta C_p(Fr,\Theta)$ = the average pressure difference coefficient across the building envelope, i.e., $(C_{pe}-C_{pin})$ averaged over the building surface $\Delta C_p(\Theta) = \Delta C_p(Fr,\Theta)$ averaged over range of Fr ΔC_p = model parameter describing $\Delta C_p(\Theta)$ averaged over Θ
Δp	pressure difference across the building envelope
ΔT	indoor- outdoor air temperature difference
ϕ	model efficiency defined as $n*\sqrt{S^2/N}$
ρ	density of air
Θ	angle (see Fig. 5)
Θ_n	angle (see Fig. 5)
ξ_L	non-dimensional leakage variable defined as ΔC_p*Fr

INTRODUCTION

The aim of this report is to test a number of models with experimental data on ventilation from different buildings to study the behaviour of models under varying conditions. The models are then considered rather as descriptive models than as predictive ones.

The possibility of using the models for predictive purposes will be associated with the physical interpretation of the model parameters and their stability, which can be checked by a determination of the parameter values by fits to different data sets.

In this Report we have not tried to find "the" very best model to describe measurements from experiments on the rate of air change in residential buildings with natural ventilation. We have investigated a set of models where the properties of the models vary. These models have been confronted with data from a set of experiments where the studied buildings are not of the same kind.

The number of free parameters of each model has been varied to study the efficiency of the model in describing experimental data. The effect of including in these simple models a wind direction dependent correction has also been studied.

The physical significance of the model parameters is partly inferred from a numerical exercise using information about the pressure distribution on the building surface obtained in a wind tunnel study.

In an Appendix the properties of some of the models are derived in a general way using dimensionless entities. These models are members of a class of models that are constructed by defining the location of openings. It is shown that models of this kind are the most efficient ones as long as simple models are considered.

THE EXPERIMENTS

In a study of this kind it will only be possible to include the results from a limited number of experiments in the data set. These experiments will have to be chosen with great care. In the selection of experiments we have been looking for experiments fulfilling one or more of the following criteria:

1) The experiments should be reliable ones with as small errors as possible

2) There should be variation between the chosen experiments regarding the type of building studied, the air- tightness of the building, the building design, the geographical location of the building, and the exposure of the building.

3) The data records should include measurements from periods with large variation in wind speed, indoor- outdoor temperature difference, and wind direction.

4) Data should be available from periods when there are addditional openings present like open windows, vents or ventilation slots.

5) The measurements should not have been carried out over such a prolonged period that there are reasons to believe that the physical properties of the studied building have changed.

6) The results of the experiments have been published

A schematic description of the six chosen experiments is given in Table 1) (ref. 1,2,3,4,5,6, and 7). They include one two storey (1) and one one- storey (2) detached house, two row-houses (3 and 4+7), one flat in a multi- storey residential building (5), and a test box on top of three- storey building (6).

TABLE 1

LIST OF EXPERIMENTAL INVESTIGATIONS

Ref. nr	Type of building	Range of v	Range of ΔT	Range of Θ
1	Two-storey detached houses built in rows close to one another.Sheltered site. No data for windows.Canada	0 - 8 m/s	6 - 38 K	45
2	One storey detached houses.Suburban setting. No data for windows. Data also for no heating (negative T). Belgium.	2 - 7 m/s	-4 - 20 K	50
3	Two- storey row- houses. Sheltered site. Data for open vents. Only one wind direction. The UK.	0 - 9 m/s	2 - 17 K	0
4+7	Two- storey row- houses. Sheltered site for most wind directions. Suburban setting. Data available for several open window combinations. The US.	0 - 14 m/s	12 - 25 K	100
5	Flat in a 4-storey building with 3 external walls.Data for open vents and average dependence of pressure on exposed walls on wind direction available. The Netherlands.	0 - 15 m/s	-4 - 20 K	260
6	Test box with three exposed sides on top of three- storey building. Data for windows and vertical and horizontal ventilation openings.No data for wind direction. Germany.	0 - 6 m/s	0 - 25 K	-

THE MODELS

A discussion on the underlying assumptions for some of the investigated models can be found in the Appendix. A short description of the models can be found in Table 2).

Models A and B are not expected to give a very good description of data, but have been included to give a frame of reference for what can be achieved by using models which take into account only the wind speed or the temperature difference.

The models C, D and E are ad hoc models for which no theoretical justification can be given. A variety of such models can be applied to describe experimental findings (a number of such models have been confronted with data from one experiment in ref. 8). These models have the advantage that they are linear in the parameters, which facilitates the analysis, one can, e.g., use linear regression techniques.

The models F, G, and H are of a different kind. Here it is possible to tell exactly what approximations have been made and what are the assumptions about the location of the openings. The parameters of these models can be given a physical interpretation. The models can be expressed in terms of non-dimensional parameters and variables which can be scaled to give the models the same asymptotic behaviour when the air change is driven by either aeromotive forces or stack effects. A comparison of this kind is given in Fig. 1).

In the Appendix it is stated under what conditions the dimensionless infiltration rate $I\gamma$ is a function of the Froude number Fr only . In fig. 2) data from the chosen six experiments are plotted in the form of the (scaled) dimensionless rate of air exchange versus the (scaled) Froude number. The assumption that all points lie on a universal curve is consistent with data if an error, including experimental errors, of the order of 20% is allowed for. An analytical expression for this curve can not be found with errors of this size, but the shape of the band of data in the plot indicates that it ought to be possible to construct models which give a

good fit to data using only two free parameters.

A parameter often varied is the exponent γ which enters any model if the flow through an opening is assumed to be proportional to the pressure difference across the opening raised to the power γ. If it is assumed that the combined effect of all openings results in a rate of air change proportional to the average pressure difference raised to the same power, one can estimate the value of the parameter γ. Assume that the air change per hour, ACH, is given by $ACH=K_v*v^m$ when the air exchange is driven mainly by wind pressure, and by $ACH=K_{\Delta T}*\sqrt{\Delta T}^{\,m}$ when the air exchange is driven mainly by stack effects. By picking data from periods when one of these situations is prevailing, the value of m has been determined for the six chosen experiments assuming that the constants K_v and $K_{\Delta T}$ may differ between the experiments, but the value of m is common to all experiments.

The results are presented in fig. 3 and 4. For the case when wind pressure is dominant one obtains $m=1.04 \pm 0.05$, while when stack effects are dominating one obtains $m=0.97 \pm 0.10$. This indicates that a reasonable value of $\gamma=m/2$ would lie between 0.45 and 0.55. If the value of the parameter γ could be fixed, the models would contain one parameter less.

Anticipating the presentation of the results of this investigation, it can be stated that most models are not very sensitive to exactly what value of γ is chosen as long as it lies between 0.4 and 0.7, a good fit to data can still be obtained by varying other parameters of the models. However, the best fit is in general obtained for a value of γ close to 0.5.

In the section containing the results we present the results for three variants of each model, either the value of γ has been fixed to 0.5 or 0.7, or γ has been treated as a free parameter whose value is determined by a fit to experimental data.

One way to test the physical significance of the model parameters is to compare their values as determined from different experimental conditions. For example one can determine the parameter values for two different configurations of openings of a building. If the value of some parameters are determined from a fit to data on the rate of air change when there are no windows or vents open, and they are then determined anew using a data set including events when windows or vents have been opened, the values of physically significant parameters should be stable. The model then has to include also parameters describing the presence of an additional opening. For this reason we have included among the chosen experiments some where data on the rate of air exchange exist for the situation when there are additional openings (3, 4+7, 5 and 6).

Fits of the above kind are presented for the models F, G, and H. These models then include one parameter, α, that can be associated with the equivalent leakage area of the openings where the regular infiltration and natural ventilation takes place, one parameter, ΔC_p, that can be associated with the average wind induced pressure difference across the building, and one parameter, β, that describes the leakage area of the additional opening.

A drawback of very simple models like those discussed here is that they can not take into account the variation of the pressure distribution with wind direction. For a tilted flat plate the force in a uniform air stream is, for a large interval of the angle of incidence, approximately proportional to the area of the plate projected on a plane perpendicular to the flow direction. There are examples that indicate that this may at least in some cases be true also for the average of the pressure difference across the building envelope, $p_e - p_{int}$ (see fig. 7). We have therefore investigated the effect of multiplying, for detached houses, the velocity head by a correction factor $\cos\theta_n$, where θ_n (see fig. 5) is the angle between the wind direction and the normal to the diagonal of the building floor plan, i.e., the correction factor for the wind speed becomes $\sqrt{|\cos\theta_n|}$. For a rowhouse the corresponding correction factor will be equal to $\cos\theta$, where θ is the angle between the wind direction and the

normal to the building facade. This means that the wind speed is taken to zero when the direction of the free wind is parallel to the building facade.

If the real pressure coefficient were known for different wind directions, one could calculate the resulting pressure difference across the building envelope for different models and thereby reduce the number of parameters by one. However, measurements of this kind combined with measurements of the rate of air change are very rare. For the chosen six experiments data on the external pressure are available only for ref. 5. For this experiment we have studied the effect of including in the model information about the resulting pressure difference across the building envelope.

To sum up, we have when choosing models considered models having some of the following properties:

1) Models where the number of free parameters can be varied.

2) Models where the maximal number of free parameters varies between the different models.

3) Models that can easily incorporate the effect on the resulting rate of air change of the presence of an additional opening like a window or a vent.

4) Models where the parameters can be given a physical interpretation.

5) Models that can be expressed in terms of non-dimensional entities.

TABLE 2

LIST OF STUDIED MODELS

MODEL	DESCRIPTION OF MODEL	PARARAMETERS
A	Only temperature dependence $a^*(\Delta T)$.	a and γ
B	Only wind dependence $a^*(v^2)^\gamma$. Equivalent to the assumption that the flow through openings is proportional to the pressure difference across opening raised to the power γ, with two openings of the same size, one in the windward and one in the leeward facade.	a and γ
C	Expression linear in a power of the wind speed and the temperature difference, $a^*(\Delta T)^\gamma+b^*(v^2)^\gamma$.	a, b, and γ
D	Linear expression containing terms proportional to a power of the temperature difference and the wind speed and a constant, $a^*(\Delta T)^\gamma + b^*(v^2)^\gamma +c$	a, b, c, γ
E	As D, but the constant is replaced by an interference term between the wind speed and the temperature difference $a^*(\Delta T)^\gamma + b^*(v^2)^\gamma + c^*(\Delta T^*v^2)^\gamma$.	a, b, c, γ
F	$(a^*\Delta T + b^*v^2)^\gamma$. Equivalent to assuming that the flow through an opening is proportional to the pressure difference across the opening raised to the power γ, with one opening at bottom of windward side and one equally big opening at top of leeward side.	a, b, and γ
G	As F but with continuous distribution of openings on windward and leeward sides.	Structure as F (see App.)
H	As F and G but with four equally big openings at top and bottom of windward and leeward sides.	Structure as F (see App.)

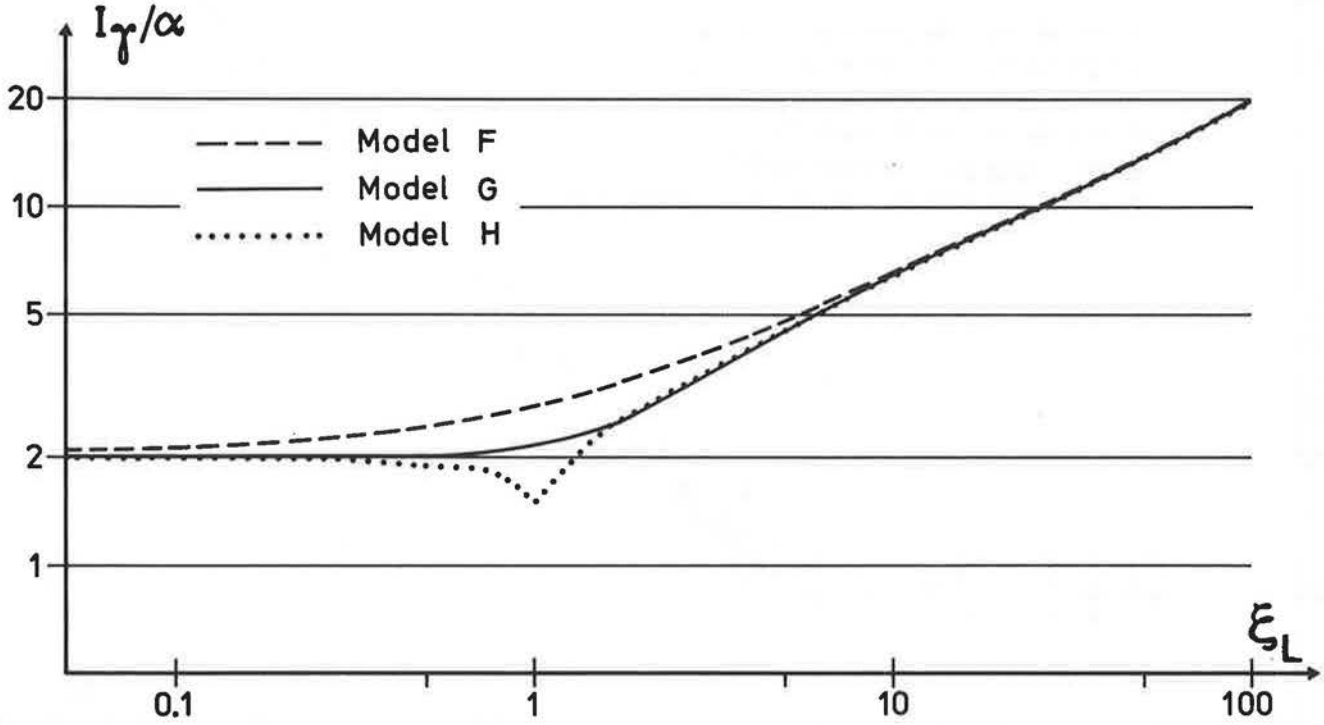

Fig 1 A comparison of the models F, G and H. The parameters have been chosen so the models have the same asymptotic behaviour for small and large values of the leakage variable ξ_L. The dimension-less infiltration rate I_γ has been scaled by the non-dimensional leakage area α.

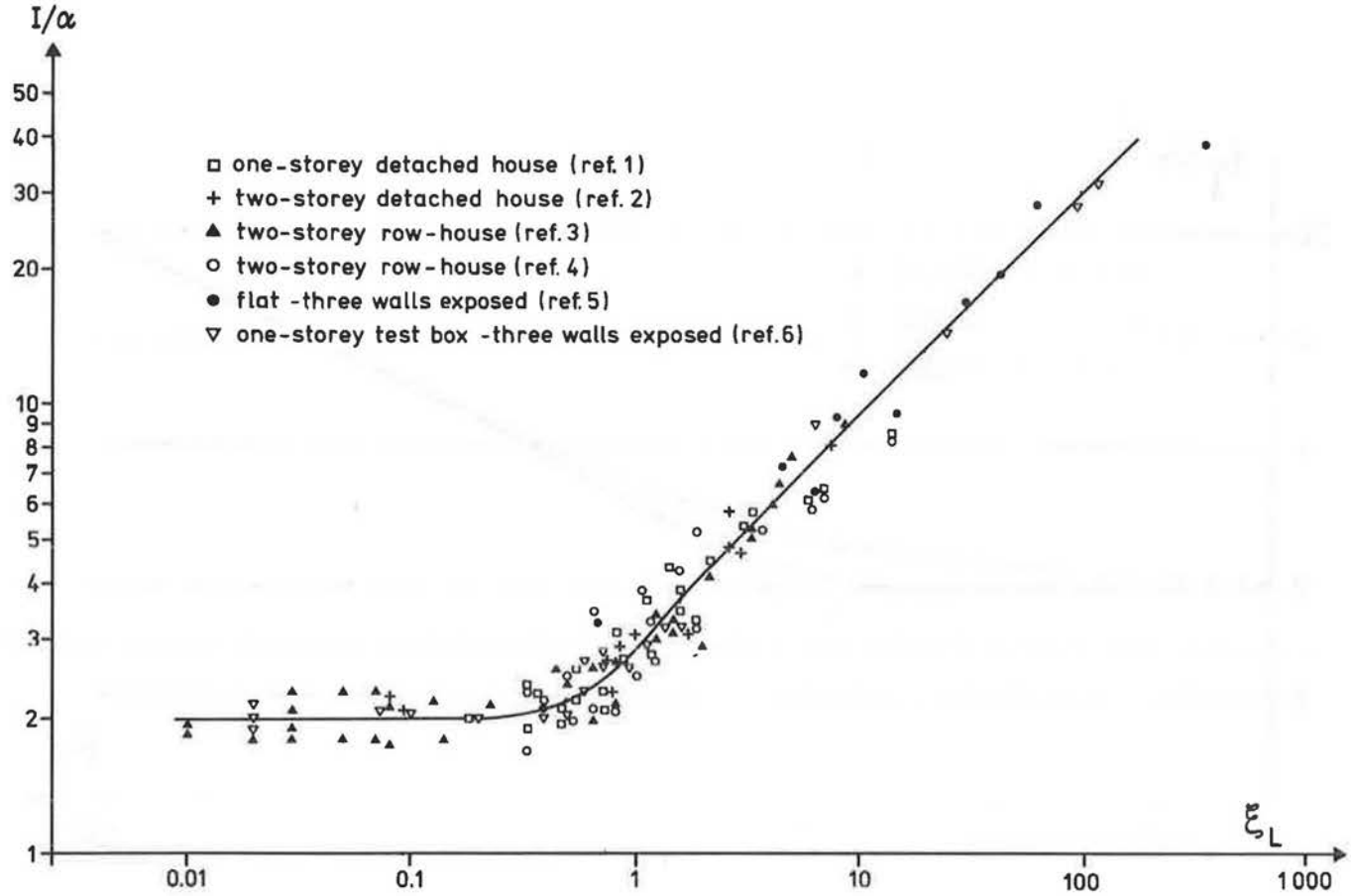

Fig 2 Experimental data for the non-dimensional infiltration rate I_γ scaled by the equivalent leakage area α, versus the leakage variable ξ_L. The curve is a fit to data using model G. The value of the exponent γ has been fixed to 0.5. Data points lying close to one another have not been included in the figure. It should be noted that data points belonging to the same experiment can be moved an equal amount in the vertical direction by taking another value of the parameter α, and in the horizontal direction by taking another value for the parameter ΔC_p.

A NUMERICAL EXERCISE

To see if there are any theoretical reasons why simple models like those discussed in the previous section and in the Appendix should work at all, one can study the behaviour of the models when applied to different buildings. One then has to specify:

1) The distribution of the external pressure over the building surface

2) The location and size of all openings

3) The presence of internal resistances to air flow

4) The properties of the mechanical ventilation system

Here we will not apply the models to buildings divided in cells with a resistance to air flow between them, or to buildings equipped with forced ventilation systems. It then remains to specify the first two properties listed above.

The location of openings varies much between buildings. One would therefore have to specify a large set of opening configurations if one wanted to study all possible types of buildings, and this would lead to more complex models than those discussed in this Report. Here we will only consider configurations of openings corresponding to those used in the definition of the models F, G, and H. These configurations are simple ones, yet they are very different. It is still possible to see if the models are applicable even if they do not take into account the actual large variations of wind pressure over the building surface. It remains to specify the pressure distribution.

There do not exist many full- scale measurements of the external pressure on buildings with a large variation in wind speed and wind direction, and with a dense arrangement of measurement points on the building envelope. However, such data are available from studies in wind tunnels including variations

in building design, building environment and wind direction, and with the building surface divided into more than 100 elements for which the pressure coefficient, C_{pe}, is known (see ref. 9).

For this exercise we have chosen a two-storey house where the upper storey is smaller than the lower one to avoid the too simple case of a parallel epipedic building (see fig. 5). In this exercise we have tested:

1) Assuming a model specifying a certain configuration of openings, e.g., openings evenly distributed over the building surface like in model G; can the underlying assumption of the models F, G, and H (see Appendix), that the internal pressure coefficient is relatively independent of wind speed, temperature difference and wind direction, be verified?

2) If the average pressure difference coefficient across the building envelope, $\Delta C_p(Fr,\theta)$, is calculated and averaged over all wind directions θ and Froude numbers Fr, using information about the distribution of the pressure coefficient over the building surface, and this averaged pressure difference coefficient is used in a model for the value of the parameter ΔC_p, does the model predict a reasonable rate of air change?

3) Does the outcome of the tests 1) and 2) depend on the choice of the value of the exponent γ?

Some results are given in fig. 6, 7 and 8. In fig. 6 we give the variation of the resulting internal pressure coefficient C_{pin} and the resulting average pressure difference coefficient $\Delta C_p(Fr,\theta)$ across the building envelope as a function of the Froude number Fr for different wind directions. The data in fig. 6 refer to the model G with a value of the exponent γ equal to 1/2.

The value of $\Delta C_p(Fr,\theta)$ is remarkably constant as a function of Fr for all wind directions, but its average value differs somewhat between the wind directions.

In fig. 7 we give the calculated pressure difference coefficient $\Delta C_p(Fr,\theta)$ averaged over all values of Fr, $\Delta C_p(\theta)$, as a function of the wind direction. The average value of $\Delta C_p(\theta)$ is rather constant for angles up to 60°, but then it drops to about half its maximal value. In fig. 7 we have also included a curve proportional to the wind direction dependent correction factor to the model parameter ΔC_p discussed in the previous section. This exercise indicates that such a correction is possibly an efficient one. However, as will be seen in the next section, this does not seem to be the case in practice for detached houses.

In fig. 8 we give the resulting variation of the predicted rate of air change when all wind directions are considered along with the rate of air change predicted by the models F and G when the procedure, outlined under 2) above, for the determination of the (wind direction independent) parameter ΔC_p has been used, and the wind speed has been assumed to vary between 0 and 10 m/s, and the temperature difference has been assumed to vary between 5 and 40 K.

Assuming an equal probability for the occurence of wind speed and temperature difference in these intervals and an equal probability for the occurence of all wind directions, both models would predict a rate of air change with an average error of about 20 %. If the building considered in this exercise had been a real one and an experiment had been carried out, one would, assuming that the experimental error can be neglected, have observed an error smaller than 20 %. This is due to the larger probability for the occurence of certain wind speeds, wind directions, and temperature differences.

Results similar to those given in the fig. 6, 7, and 8 have been obtained for all models F, G, and H and for values of the exponent γ equal to 0.5 and 0.7. However, for a value of γ equal to 0.7 the average error is larger than 25 %.

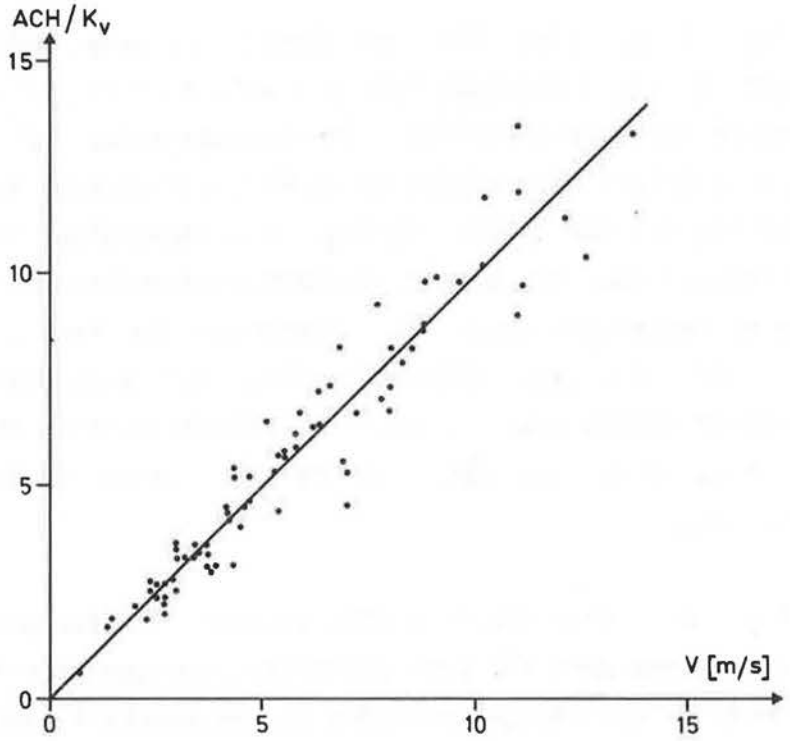

Fig 3 A fit to data on the air change per hour (ACH) for data where the Froude number, Fr, is large. Data from ref 1-6. ACH has been assumed equal to ACH = $K_V \cdot v^m$, where v is the wind speed, the exponent m is the same for all experiments but the constant K_V may vary between the experiments. The best fit gives a value m = 1.04 ± 0.05.

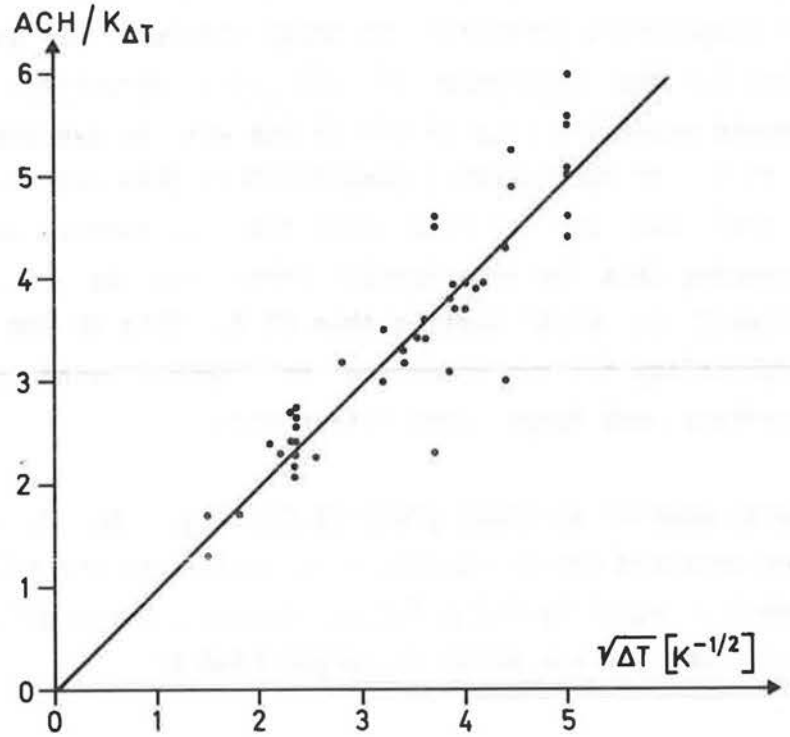

Fig 4 A fit to data on the air change per hour (ACH) for data where the Froude number is small. Data from ref 1-6. The air change per hour has been assumed given by ACH = $K_{\Delta T} \sqrt{\Delta T}^m$ where ΔT is the indoor-outdoor temperature difference, the parameter m is the same for all experiments but the value of the constant $K_{\Delta T}$ may differ between the experiments. The best fit gives a value m = 0.97 ± 0.10.

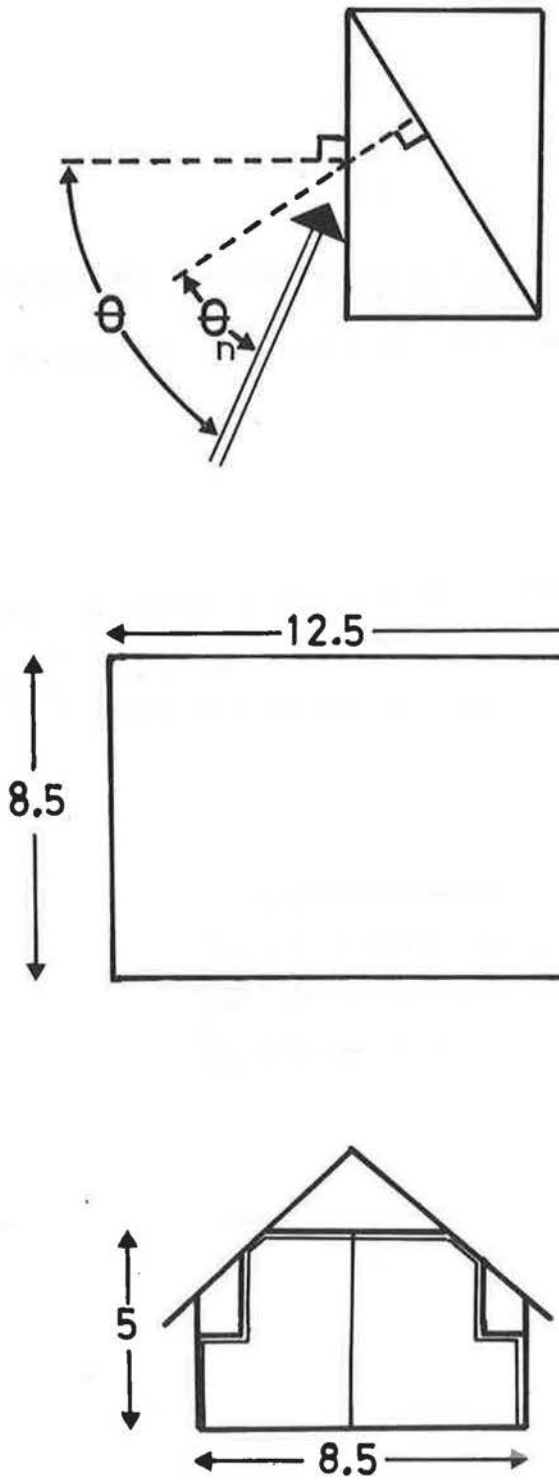

Fig 5 Top: The angle θ between the wind direction and the normal to the front of the building, and the angle θ_n between the wind direction and the normal to one of the diagonals of the building floor.

Middle and bottom: Design of the two-storey detached house considered in the section "A Numerical Exercise".

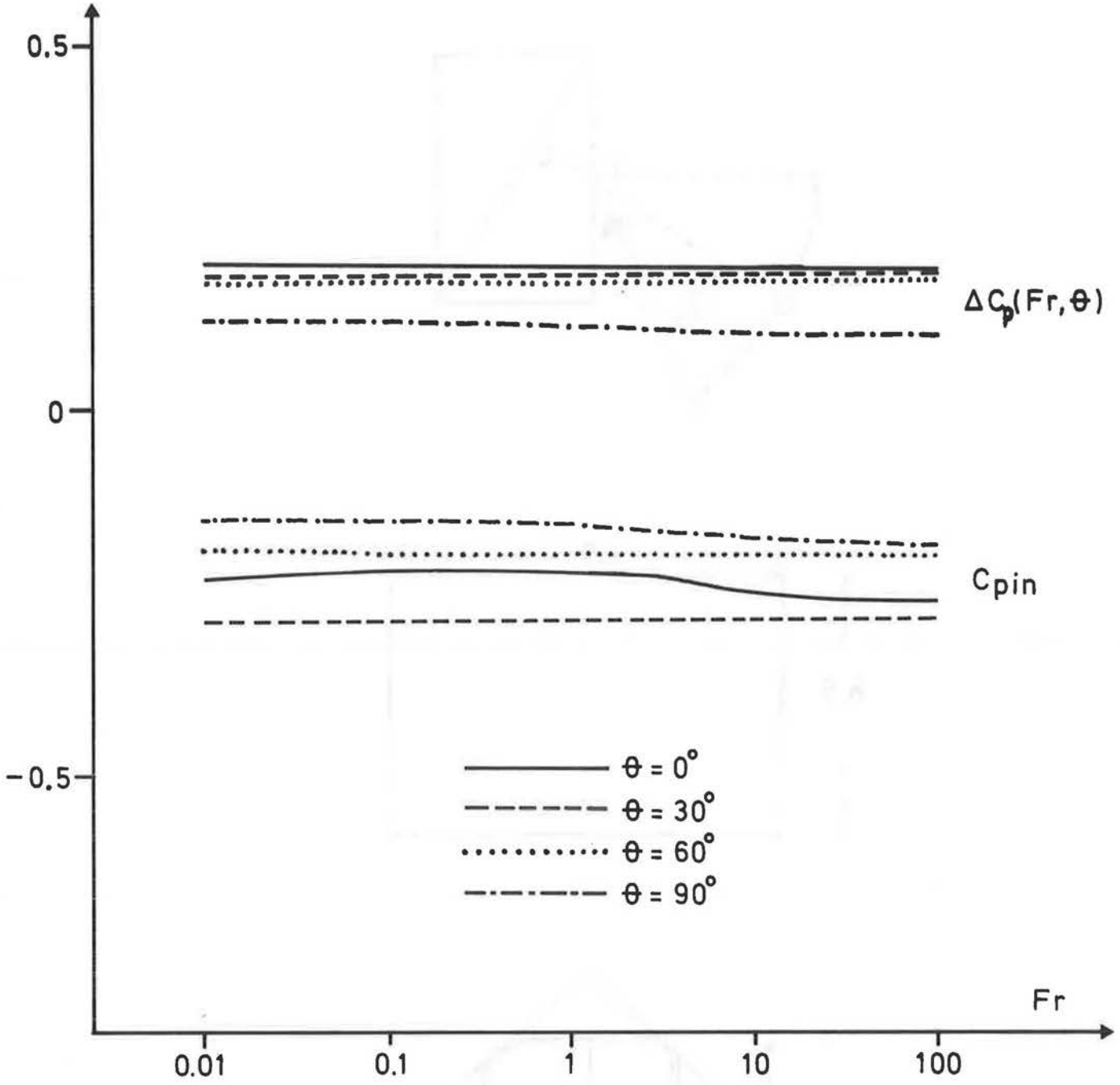

Fig 6 The internal pressure coefficient C_{pin} and the average pressure difference coefficient ΔC_p (Fr, θ) versus the Froude number, Fr, for different wind directions, θ. The curves have been obtained using model G with a value of the exponent γ equal to 0.5. The building considered is the one of Fig 5. The building environment corresponds to a densely built suburban area. The range of Fr corresponds to a range of wind speed 0.5 - 10 m/s and an interval of the indoor-outdoor temperature difference 5 - 40 K.

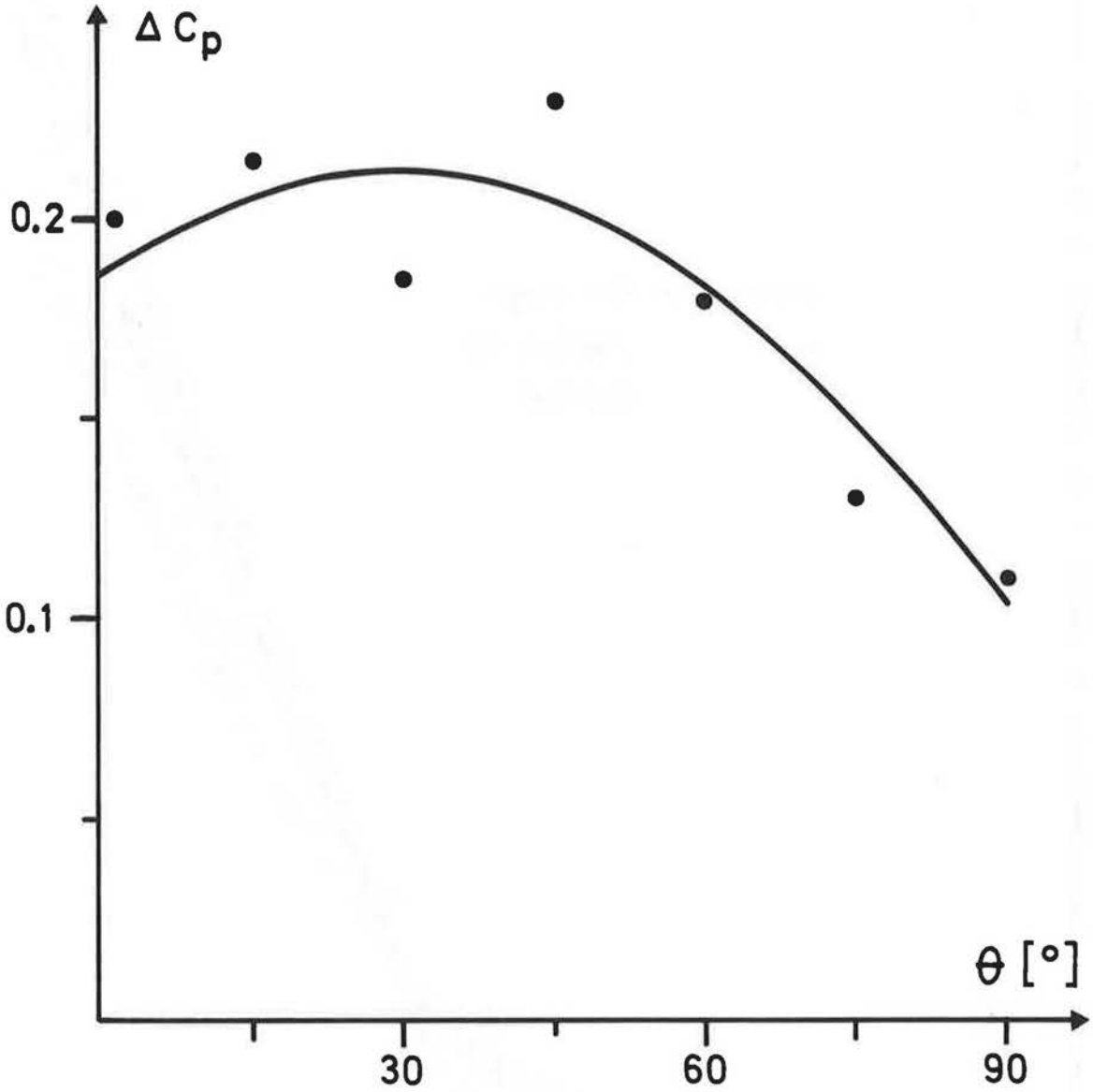

Fig 7 The average pressure difference coefficient ΔC_p (Fr, θ) averaged over the range of Froude number, Fr. The model, building, and other circumstances are those given in Fig 5 and 6. The curve is proportional to $|\cos \theta_n|$, where θ_n is the angle defined in Fig. 5.

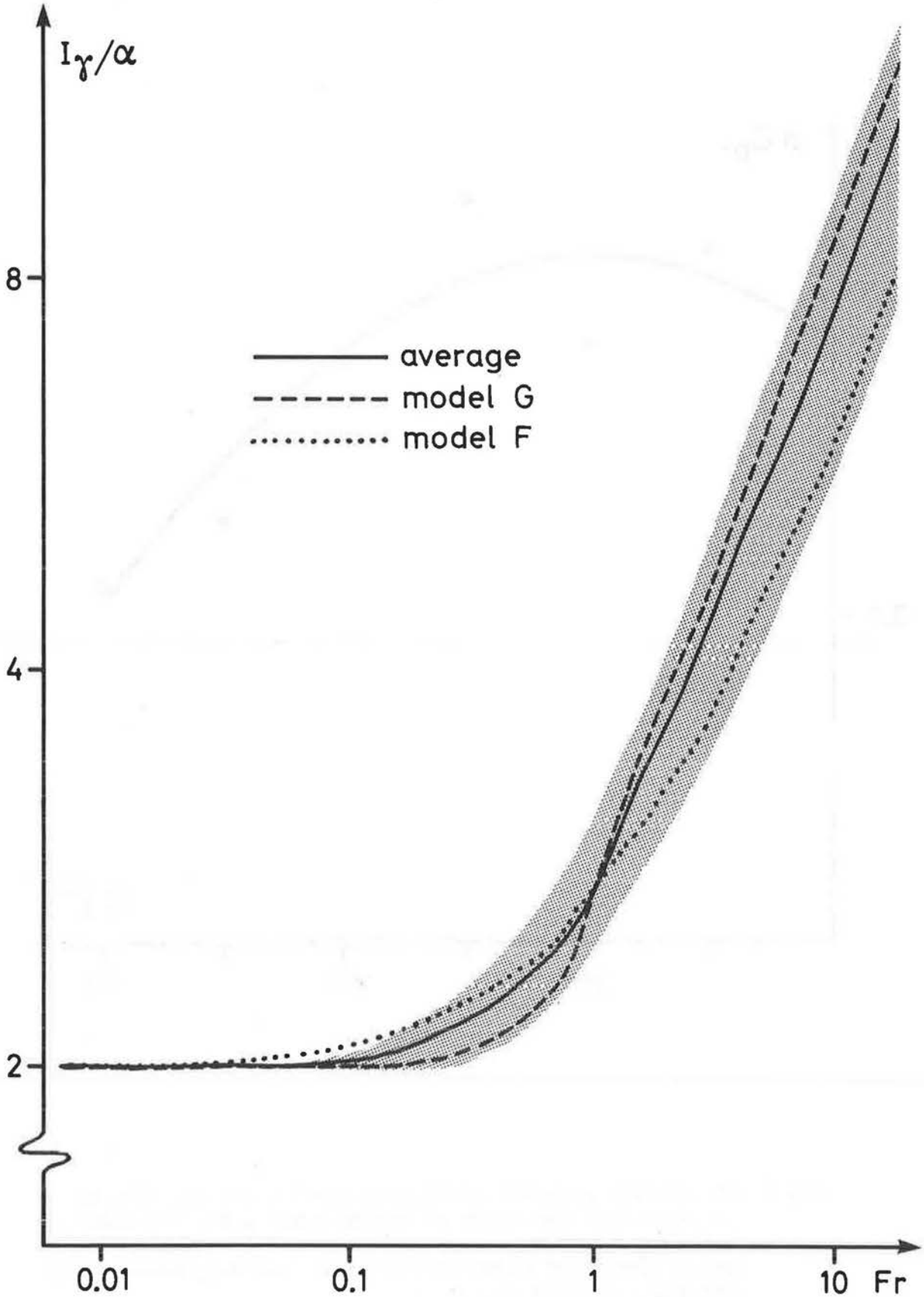

Fig 8 The non-dimensional infiltration rate I_γ scaled by the equivalent leakage area, α, versus the leakage variable ξ_L for the calculations performed in the section "A numerical Exercise". The dotted area contains all data computed for the wind speeds and temperature differences given in Fig. 6, and for all wind directions. The full-drawn curve is the value of I_γ/α averaged over all wind directions, the hatched curve is the prediction of the (wind direction independent) model G and the dotted curve the prediction of the model F.

RESULTS OF FITS

When performing the fits one first has to choose the object function to minimize. As the rate of air change is much larger when there are open windows, and we prefer a fit where the sum of the relative error of all data points is minimized instead of the sum of the absolute errors, we have as objective function chosen the function S^2 where

$$S^2 = \Sigma \, |\ln ACH(experimental) - \ln ACH(model)|^2$$

The results are presented in the Tables 3 through 6. As the objective is to study the efficiency of the models, the results in Table 3 and 4 are given in terms of a measure of efficiency of the models, ϕ, defined as

$$\phi = n * \sqrt{S^2/N}$$

where n is the number of free parameters and N is the number of data points. Without going into details it will just be mentioned that this measure of the model efficiency, for a model linear in the parameters, can be shown to have an upper bound as a function of the number of free parameters, and the value of n for which the model is considered most effecient is the value of n for which ϕ has its minimum.

From Table 3 it is rather evident that the models F,G, and H are more efficient than any of the models A-E. It is also clear that a value of γ=0.5 is to be preferred to a value of 0.7. This is in agreement with the results of the procedure outlined in the section "The Models" to determine the value of γ.

The wind direction dependent correction of the parameter ΔC_p considered in the above mentioned section does not give any improvement for the fits to data from the experiments 1 and 2 (detached houses). However, for the experiment of ref. 4 (row-house) the improvement is quite large, the average error drops by 30 or 40%.

The use of data on the external pressure in a fit to data from the experiment 5 also gives a clear improvement. The measure of efficiency for the models G and H drops by a factor of 3, corresponding to a decrease of the average error by about 40%.

Letting the exponent γ be a free parameter does not improve the efficiency of the models compared to when γ is given a fixed value of 0.5, but of course the average error is smaller.

In Fig. 2 we five the results of the fit using model G. The fits using the models F and H produce similar results.

In Table 4 we give the results of the fits to experiments with additional openings. Because of the small building volume of ref. 6, we have in this case only considered data on the rate of air change when there are additional openings in the form of vertical or horizontal ventilation slots.

As shown in Table 4, the inclusion of information about the external pressure also in this case reduces the average error by about 40%.

The efficiency of the models is only somewhat improved if all free parameters are determined simultaneously compared to when the parameters α and ΔC_p are determined by a fit to data with no additional openings and the parameter β, the parameters α and ΔC_p being kept fixed, is determined by a fit to data on the rate of air change when there are additional openings. In Fig. 8 and 9 we give the results of the fits to the experiments 3 and 7.

In the fits the parameter values will of course vary between the studied buildings. The parameter α varies from less than $1.5*10^{-4}$ for the most airtight building up to nearly $2*10^{-3}$ for the most leaky one, i.e. by more than a factor of 10. The parameter β takes a value for open windows and vents and ventilation slots corresponding to a discharge factor having a value between 0.3 and 0.45. This is a smaller value than even

the smallest conventional value of the discharge factor, about 0.6, for flow through an orifice. However, it is known that due to imperfect mixing of the room air with the air entering through the opening this lower value is about what is to be expected.

The stability of the parameters when the parameter values of the fitting procedures outlined above are compared to one another is given in Table 5. From the analytical expressions for the models F, G, and H given in the Appendix, one would expect these models not to be very sensitive to changes in the parameter ΔC_p, but rather sensitive to changes of the parameters α and β as I_γ contains terms directly proportional to α and β. This expectation is confirmed by the results of Table 5. The parameters α and β are quite stable, but the value of the parameter ΔC_p can be varied up to 50% and still hardly affect the efficiency of the model. The minimum of the object function lies in a region which is very flat in the ΔC_p dimension. To assess the stability of this parameter one would have to make fits to data sets where the experimental error is much smaller than at present.

Finally we give in Table 6 the average errors when applying the models F, G, and H to the experiments 1-6. For experiment 4 the wind direction dependent correction of the parameter ΔC_p has been applied. The results are given for various values of the exponent γ. It can be seen that if γ is given a fixed value of 1/2, the average error in the description of rate of air exchange is about 20%, while if γ is treated as a free parameter the average error is reduced to about 15%. This is rather satisfactory as the experimental error is expected to be responsible for an error of about 10%. However, as mentioned above, the efficiency of the model is not much improved by letting the exponent γ be a free parameter.

The magnitude of the error is also about the same as the one found in the exercise, and an error of this size is probably to be expected for models that do not make use of any information about the pressure distribution over the building surface, and do not take into account the wind direction (except in a rather crude way for a row-house).

TABLE 3

MEASURE OF EFFICIENCY ϕ FROM FITS WITH NO WINDOWS

MODEL	VALUE OF γ	NR OF PAR	EXP NR 1	2	3	4	5	6	AVERAGE
A	0.7	1	.42	.39	.38	.47	.70	.77	.52
A	0.5	1	.37	.32	.35	.46	.57	.58	.44
A	free	2	.45	.40	.47	.61	.59	.45	.37
B	0.7	1	.43	.22	.95	.36	.40	.87	.54
B	0.5	1	.33	.17	.63	.32	.24	.60	.38
B	free	2	.37	.22	.32	.42	.27	.39	.33
C	0.7	2	.15	.21	.17	.39	.43	.32	.28
C	0.5	2	.23	.19	.19	.41	.28	.26	.26
C	free	3	.15	.22	.19	.45	.29	.29	.27
D	0.7	3	.23	.26	.21	.56	.42	.33	.34
D	0.5	3	.34	.28	.29	.59	.38	.35	.37
E	0.7	3	.22	.30	.17	.51	.99	.99	.53
E	0.5	3	.30	.27	.26	.52	.40	.38	.36
F	0.7	2	.13	.21	.16	.39	.44	.27	.27
F	0.5	2	.20	.19	.15	.41	.29	.16	.23
F	free	3	.14	.21	.17	.44	.31	.18	.24
F angle dep. ΔC_p	0.7	2	.16	.25	-	.27	-	-	.23
F " " "	0.5	2	.24	.24	-	.28	-	-	.25
F " " "	free	3	.15	.24	-	.28	-	-	.22
F pressure known	0.5	1	-	-	-	-	.17	-	-
G	0.7	2	.18	.22	.21	.48	.53	.22	.31
G	0.5	2	.17	.21	.15	.45	.36	.11	.24
G	free	3	.16	.20	.15	.47	.30	.11	.23
G angle dep. ΔC_p	0.7	2	.18	.24	-	.33	-	-	.25
G " " "	0.5	2	.17	.23	-	.30	-	-	.23
G " " "	free	3	.16	.23	-	.29	-	-	.23
G pressure known	0.5	1	-	-	-	-	.11	-	-
H	0.7	2	.19	.23	.25	.56	.53	.24	.33
H	0.5	2	.14	.22	.18	.48	.38	.25	.27
H	free	3	.14	.22	.17	.48	.34	.13	.25
H angle dep. ΔC_p	0.7	2	.19	.25	-	.36	-	-	.27
H " " "	0.5	2	.15	.26	-	.31	-	-	.24
H " " "	free	3	.15	.25	-	.31	-	-	.24
H pressure known	0.5	1	-	-	-	-	.12	-	-

TABLE 4

MEASURE OF EFFICIENCY ϕ FROM FITS WITH WINDOWS

MODEL	VALUE OF γ	NR OF PAR	EXP. REF. NR 3	4+7	5	6 horizontal	6 vertical	AVERAGE
F	0.5	2+1	.19	.35	.49	.54	.53	.42
F	0.5	3	.19	.35	.46	.41	.44	.37
F pressure known	0.5	1+1	-	-	.40	-	-	-
F " "	0.5	2	-	-	.39	-	-	-
G	0.5	2+1	.20	.39	.49	.44	.43	.39
G	0.5	3	.19	.37	.47	.35	.33	.34
G pressure known	0.5	1+1	-	-	.28	-	-	-
G " "	0.5	2	-	-	.28	-	-	-
H	0.5	2+1	.20	.40	.50	.56	.53	.44
H	0.5	3	.19	.36	.48	.47	.32	.37
H pressure known	0.5	1+1	-	-	.30	-	-	-
H " "	0.5	2	-	-	.29	-	-	-

Notes to Tables 3 and 4

1) The models and experiments are those given in Tables 1 and 2.
2) "VALUE OF γ." is the value of the exponent γ in the fit to data
3) "NR OF PAR" is the number of free parameters of the model
4) "angle dep. ΔC_p" refers to the case when the parameter ΔC_p has been multiplied by a wind direction dependent correction factor as decribed in the section "The Models".
5) "pressure known" refers to a fit where information about the pressure coefficient C_{pe} has been used in the fit
6) For the experiment 6 "horizontal" and "vertical" in Table 4 refers to a fit where the additional openings consist of respectively horizontal and vertical ventilation slots.

TABLE 5

CHANGE OF THE PARAMETER VALUES

The change of the parameters value refers to the change when the values of the parameters α and ΔC_p are first determined by a fit to data when no windows are open and the value of β is then determined by a fit to data for open windows, compared to when the values of all parameters are simultneously determined by a fit to the whole set of data. The change is given in %.

MODEL	PARAMETER α	ΔC_p	β
F	14	50	13
G	12	38	3
H	12	50	6

TABLE 6

AVERAGE ERRORS OF PREDICTED VALUES OF ACH IN FITS

The errors are given in %

γ is the exponent of the pressure difference

MODEL	γ= 0.5	0.7	free
F	25	28	17
G	25	32	16
H	29	35	17

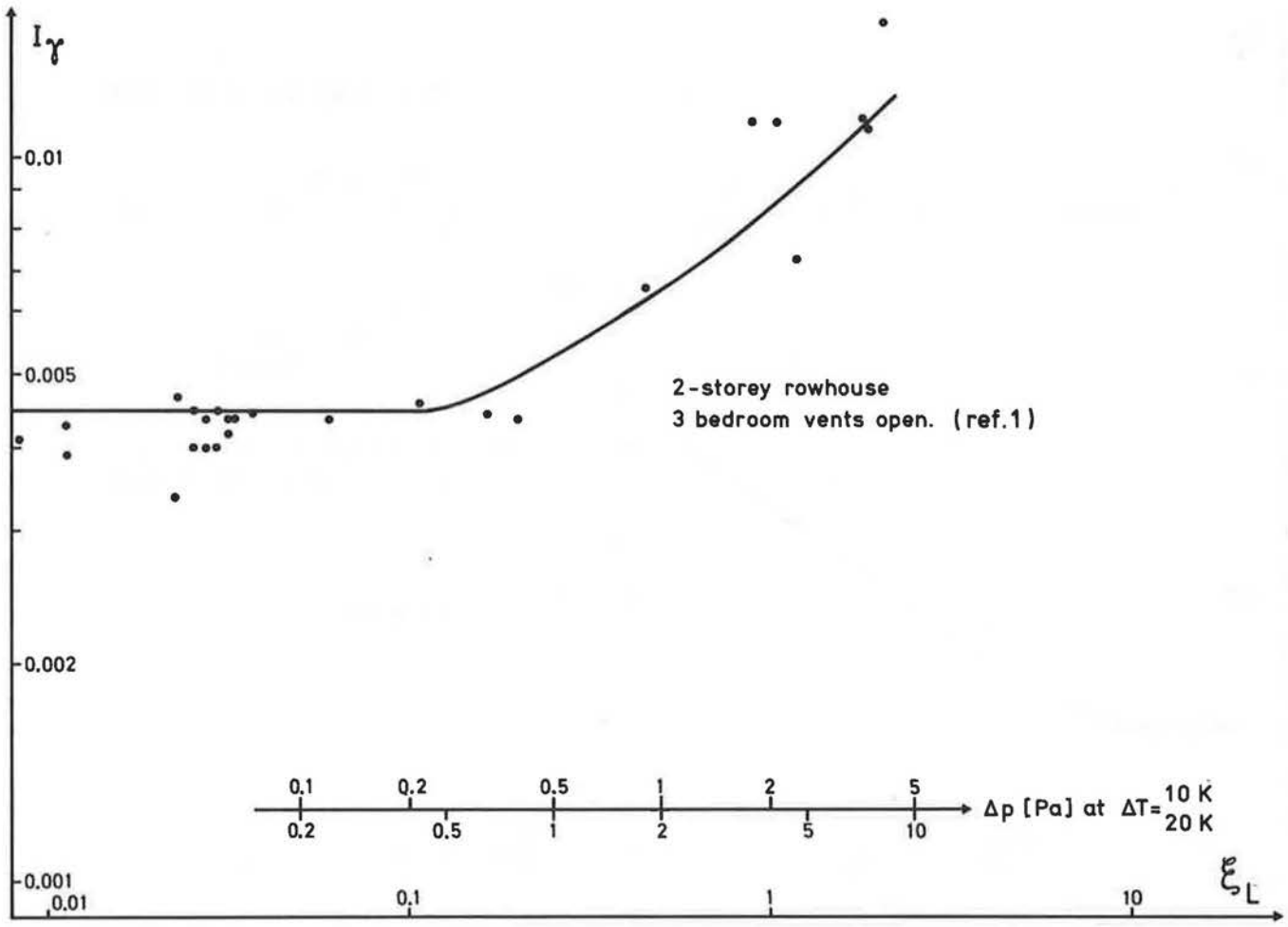

Fig 9 The non-dimensional infiltration rate I_γ versus the leakage variable ξ_L for data on the rate of air change with open vents. Data from ref 3. The curve is the best fit of model G.

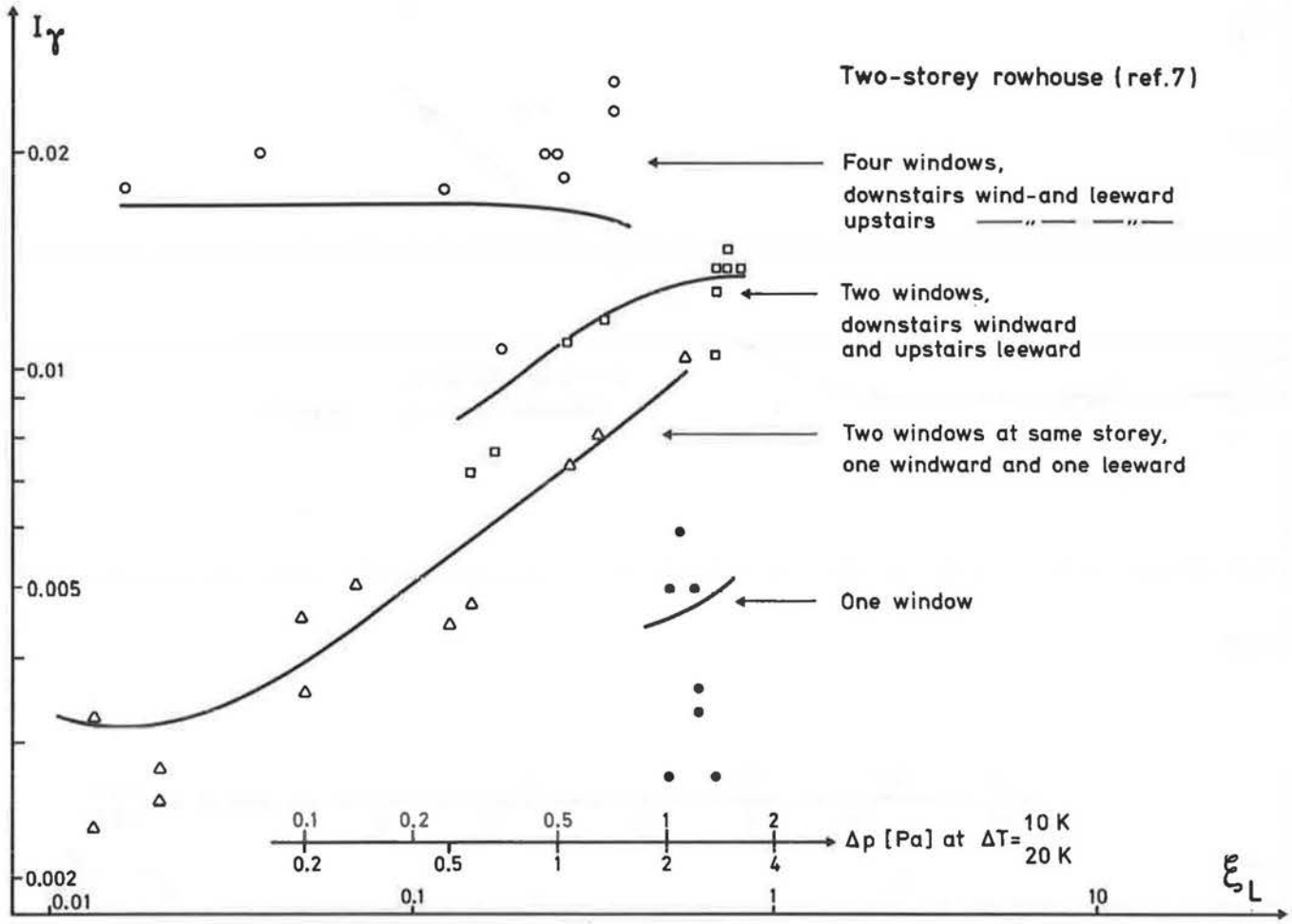

Fig 10 The non-dimensional infiltration rate I_γ versus the leakage variable ξ_L for data on the rate of air-change with open windows. Data from ref 7. The curves are the best fit using model G (the parameter values are the same for all configurations of open windows).

CONCLUSIONS

1) The most efficient models are those for which the non-dimensional rate of air change is a function of the Froude number Fr only and the model is defined by specifying the location of openings. Numerical exercises indicate that the cause of this good efficiency is associated with the fact that, given the approximations of the model, such models take into account the internal pressure in a theoretically correct way. The behaviour of the internal pressure for varying wind speeds and temperature differences is revealed by the introduction of the internal pressure coefficient C_{pin}. Numerical exercises indicate that C_{pin} is rather independent of the Froude number Fr.

2) The models having the properties mentioned above (F, G, and H) are about equally efficient in describing the experimental data, possibly with a small preference for model G. The average error is about 20 % when two free parameters are used, one describing the leakiness of the building and one associated with the average wind pressure coefficient over the building envelope. If in addition also the exponent γ is allowed to vary, the average error decreases to about 15%, but the efficiency of the models remains about the same. If the value of γ is fixed, the best model efficiency is obtained by giving γ a value close to 1/2.

3) The inclusion of a wind direction dependent correction for the parameter ΔC_p, associated with the average pressure difference across the building envelope, in the models does not improve the efficiency for detached houses. However, for buildings having only two facades, like row- houses, a correction of this kind improves the model efficiency considerably.

4) For the experiment where data on the pressure coefficient are available, the use of this information improves the model efficiency more than any other change of the model.

5) The stability of the parameters of the models F, G, and H is very good when their values are derived from data sets obtained with differing configurations of the location of openings. A possible exception is the parameter ΔC_p but the models are relatively insensitive to changes of the value of this parameter, and no definite statement about the stability of this parameter can be given with the present experimental errors. The stability of the values of these parameters also implies that they are to be regarded as physically significant parameters.

6) The average error found in the fits, 20%, indicates that if the models F, G, or H are used for predictive purposes, and the values of the parameters can be correctly chosen, these models would predict the ACH with an average error of about 10 or 15 %. It has then been assumed that an average experimetal error of 10% can be subtracted from the error found in the fits.

7) The general conclusion is that any model where the dimensionless infiltration rate I_γ, as a function of the Froude number Fr, has such a shape that it falls within the band of data points in fig. 2, will be an efficient model in the description of data on the rate of air exchange. To improve the performance of models one must consider rather more complex models that can use information about the pressure distribution over the building surface and also its variation with wind direction. If such data are not available, and as long as the experimental error is of the order of 10%, it is doubtful whether any models more efficient than the simple ones discussed in this Report can be constructed.

APPENDIX

Part of the discussion in this appendix has been presented earlier in ref. 10) (for discussions of similar ideas see also ref. 3 and 11).

The first step in the modeling of infiltration and natural ventilation is to choose a model for how the air flow rate depends on the pressure difference across an opening. Empirical relations have been expressed in various ways depending on the kind of opening. For flow in long regular pipes and ducts the flow rate is in general expressed in terms of a power of the pressure difference, or as proportional to $(\Delta p)^{\gamma}$ where Δp is the pressure difference. It has been shown that the value of γ may depend on Δp (see ref. 12). The value of γ is known exactly only for laminar or fully developped turbulent flow in long smooth channels. It then takes respectively a value of 1 and 1/2. For flow through orifices it is common to express the flow rate as $C_d * \sqrt{\Delta p}$, where C_d, the discharge factor, in general depends on the Reynolds flow number.

Strictly speaking, none of the above two expressions can be applied to describe the flow through a small opening in a building envelope. This is due to the complexity of such openings: rough walls, varying cross section, bends, non-stationary flow, entrance effects, etc. However, it has become common to use the first of the models described above, and this one will also be used in this Report.

Consider a building with natural ventilation where the exterior pressure is known on rectangular elements of the building envelope with element nr i having a width L_i and extending in height from h^i_{min} to h^i_{max}. The exterior pressure is given in terms of the pressure coefficient of element nr i, C^i_{pe}, and a reference wind speed u, as $p_o + C^i_{pe} * \rho * u^2/2$, where ρ is the air density and p_o is a reference pressure, generally taken as the (static) pressure in the free wind at a height equal to that of the building. Denote by g the gravity constant, by ΔT the indoor- outdoor air temperature difference, by T the average of the indoor and outdoor air temperature and by p_{int} the internal

pressure of the building. Denote by h_T the thermal equilibrium height (the height at which the pressure difference across the building envelope is zero) when u is zero. The pressure difference across element i at the height z, $\Delta p_i(z)$, is then given by:

$$\Delta p_i(z) = C_{pe}^i * \rho * u^2/2 - p_{int} + \rho * g * \Delta T/T * (h_T - z) \qquad (1)$$

If the flow through an opening is assumed to be proportional to the pressure difference across the opening raised to the power γ and the equivalent leakage area of element i is denoted by α_i, the fact that the sum of the inflow and outflow of air has to be equal to zero can be expressed through the equation:

$$\sum_i \sqrt{2/\rho} * \alpha_i * L_i * \int_{h_{min}^i}^{h_{max}^i} \mathrm{sgn}(\ \Delta p_i(z)\ ) * |\Delta p_i(z)|^\gamma \, dz = 0 \qquad (2)$$

The sign of Δp_i has to be included in eq. (2) so that an inflow is counted as positive and an outflow as negative. The above eq. determines the value of p_{int}. Expressing the interior pressure in terms of the reference windspeed, u, and a coefficient, C_{pin}, the internal pressure coefficient, as $p_{int} - p_o = C_{pin} * \rho * u^2/2$, denoting by Fr the Froude number (see ref. 11), defined as the ratio of the aeromotive force to the buoyancy force:

$$Fr = T * u^2/(2 * g * h_T * \Delta T) \qquad (3)$$

and performing the integration in eq. (2), one arrives at

$$\sum_i \alpha_i L_i h_T Fr^{-\gamma}/(1+\gamma) * \{\mathrm{sgn}(X_1^i) * |X_1^i|^{\gamma+1} - \mathrm{sgn}(X_2^i) * |X_2^i|^{\gamma+1}\} = 0 \qquad (4)$$

where $X_1^i = (C_{pe}^i - C_{pin}) * Fr + 1 - h_{min}^i/h_T$ and $X_2^i = (C_{pe}^i - C_{pin}) * Fr + 1 - h_{max}^i/h_T$

To calculate the flow of air into the building one has to include in the summation only terms where X_1 or X_2 are positive. This calculation can be performed in terms of a dimensionless rate of air exchange. Denote by V the volume of the building, by L half the circumference of the building and by ACH the air exchange per hour. One can the define the dimensionless infiltration rate I_γ as:

$$I_\gamma = ACH*V*(1+\gamma)*|Fr|^\gamma/(u*h_T*L*3600) \quad (5)$$

One then arrives at the important relation

$$I_\gamma = \sum_{i+} \alpha_i*(\rho*u^2/2)^{\gamma-\frac{1}{2}}*(L_i/L)*\{|X_1^i|^{1+\gamma}-|X_2^i|^{1+\gamma}\} \quad (6)$$

where the + in the summation index indicates that only terms where X_1 or X_2 are positive are to be included in the summation. From eq. (5) it is obvious that the equivalent opening area has the dimension $|N/m^2|^{1/2-\gamma}$. From an esthetic point of view it would be appealing if γ could be taken equal to 1/2 to make α_i dimensionless. The situation regarding the multiplying factor $\alpha_i*(\rho*u^2/2)^{\gamma-1/2}$ is not quite satisfactory. If γ is not equal to 1/2, one would expect the correction to the constant α_i to depend on the pressure difference across the opening, Δp, and not on the wind velocity. This situation would not have occured had one instead described the flow rate through the opening by the model including the discharge factor. The exponent γ would then have been equal to 1/2, but instead the air change model would have become more complicated because the parameter α would have included the discharge factor, and α would then be dependent on the Reynolds number.

One can now also see what are the necessary conditions for I_γ to be determined mainly by Fr:

1) The exponent γ must be close to 1/2

2) The internal pressure coefficient C_{pin} must take approximately the same value independent of wind speed and temperature difference, except for small values of Fr, and it must also be relatively independent of wind direction. For what buildings this is the case can be answered only by experiments.

To construct simple models from the general expression (6), one has to specify the location and the size of the openings. An important class of simple models is the one where one does not have to calculate the interior pressure coefficient C_{pin} for given Fr and C_{pe}, i.e., models where the eq. (4) is automatically fulfilled. The simplest models are those for

which it is assumed that α_i, L_i and $h^i_{max}-h^i_{min}$ take the same values for all openings and the building envelope is divided into two parts with the same area, one, below referred to as the windward side, where $C_{pe}-C_{pin}$ takes a positive value and another one, below referred to as the leeward side, where $C_{pe}-C_{pin}$ takes a negative value. If one can then associate two typical or average values C^+_{pe} and C^-_{pe} with, respectively, the windward and the leeward sides, it can be shown that there are infinitely many ways to arrange the openings so that on the windward side $C^+_{pe}-C_{pin}=\Delta C_p(Fr,\theta)$ and on the leeward side $C^-_{pe}-C_{pin}=-\Delta C_p(Fr,\theta)$, where $\Delta C_p(Fr,\theta)$ can be associated with half the average wind induced pressure difference between the windward and the leeward sides and be used as a parameter of the model, denoted by ΔC_p and referred to as the average pressure difference coefficient, provided its dependence on the Froude number Fr and the wind direction θ is weak.

Here we will only consider four simple cases leading to two- or three parameter models. For simplicity we assume that the openings extend over all of the buildig surface in the lateral direction, i.e. we put $L_i = L$. For ease of notation we introduce the variable ξ_L, defined as the product of the parameter ΔC_p and the variable Fr, or

$$\xi_L = \Delta C_p * Fr \qquad (6)$$

1) First consider the case that there is one opening at the leeward side and one at the windward side, both at the same height. It is then easily shown that ACH will be proportional to $u^{2\gamma}$. This model is referred to as model B in this Report.

2) If there is one opening at the windward side at a height z_o; $z_o<h_T$, and one at the leeward side at a height $h-z_o$, where h is the height of the building, one obtains

$$I_\gamma = 2*a*(\rho*u^2/2)^{\gamma-\frac{1}{2}}*|\xi_L+1-z_o/h_T|^\gamma$$

where the factor 2 on the right hand side has been included for convenience to facilitate comparisons with the other models (see below). From the above eq. it immediately follows that in terms

of ACH this model can (for positive ΔT) be formulated:

$$ACH = (a*u^2+b*\Delta T)^{\gamma}$$

where a and b are model parameters. This model has been proposed for predictive purposes assuming that the parameters a and b are known if certain properties of the building environment and the building design are specified (14). Obviously one can always put z_o equal to 0 if the parameter values are to be determined by a fit to experimental data; the model will have the same number of parameters. This model is referred to as model F in this Report. This model should be effective if the inflow (or the outflow) of air takes place via a dominant opening like a chimney.

3) Here one assumes that the openings are evenly distributed over the windward and leeward sides. One then obtains:

$$I_{\gamma} = \alpha*(\rho*u^2/2)^{\gamma-1/2}* \{ |\xi_L+1|_+^{\gamma+1} - |\xi_L-1|_+^{\gamma+1} + |-\xi_L+1|_+^{\gamma+1} - |-\xi_L-1|_+^{\gamma+1} \}$$

where the subscript + indicates that the term is to be included in the sum only if the expression of which the absolute value is taken is positive. For positive values of ξ_L (positive ΔT) this can be written as

$$I_{\gamma} = \alpha*(\rho*u^2/2)^{\gamma-1/2} \{|\xi_L+1|^{1+\gamma} \mp |\xi_L-1|^{1+\gamma}\}$$

where the upper sign is to be used if $\xi_L - 1 > 0$. This model can also (provided a, b, and ΔT are positive) be formulated as:

$$ACH = |a*u^2+b*\Delta T|^{1+\gamma} \mp |a*u^2-b*\Delta T|^{1+\gamma}$$

where the same sign convention as above has to be applied, and a and b are model parameters. This model is referred to as model G in this Report. This model can be expected to be an effective one if the leaks are uniformly distributed over the building envelope.

4) In this model there are four openings, two on the windward and two on the leeward side. Two are placed at a height z_o and two at a height $h-z_o$. Like for 2), one can

without loss of generality put z_o equal 0. One then obtains:

$$I_\gamma = \alpha*(\rho*u^2/2)^{\gamma-1/2} \{|\xi_L+1|_+^\gamma+|\xi_L-1|_+^\gamma+|-\xi_L+1|_+^\gamma+|-\xi_L-1|_+^\gamma\}$$

$$= \alpha*(\rho*u^2/2)^{\gamma-1/2}* \{|\xi_L+1|^\gamma+|\xi_L-1|^\gamma\}$$

The above expression can also be written:

$$ACH = |a*u^2+b*\Delta T|^\gamma+|a*u^2-b*\Delta T|^\gamma$$

This model is expected to be effective when the air change takes place mainly through openings located near the ground and near the attic. This model is referred to as model H in the text.

The models described in 2), 3), and 4) all have the asymptotic properties that $I_\gamma/\alpha(\rho*u^2/2)^{\gamma-\frac{1}{2}}$ approaches 2 as Fr goes to zero and I_γ is proportional to $|Fr|^\gamma$ for large values of Fr. This is equivalent to saying that ACH is proportional to $|\Delta T|^\gamma$ for small Fr and proportional to $|u|^{2\gamma}$ for large Fr. For the models F and G, I_γ is a continuously growing function of ξ_L, while for model H I_γ has a minimum for ξ_L equal 1 (see fig. 1). Configurations of openings that produce this effect are easily constructed (see ref. 15).

These models are easily modified to include an additional opening like an open window. This is done by adding a term like those of eq. (6) to I_γ :

$$\beta*(L_i/L)*(\rho*u\ /2)^{\gamma-\frac{1}{2}} * \{|\xi_L+1-h^i_{min}/h_T|^{1+\gamma}-|\xi_L+1-h^i_{max}/h_T|^{1+\gamma}\}$$

To make a clear distinction between such additional openings and the ordinary openings of the building envelope, we denote the equivalent opening area for windows, vents and ventilation slots by β instead of α. However, if there are additional openings, the above models are more complex to use as one has to calculate C_{pin} for each particular data point.

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