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Window Air Tightness and its Influence on Energy Saving and Minimum Required Ventilation*

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The first part of the paper presents a method for establishing the conditions and an acceptance criterion for window air-tightness testing, in relation to average energy (heating) saving per winter. Wind velocity data of the Israeli meteorological station of Ashdod is used in order to demonstrate the difference between various methods for the evaluation of the 'design wind velocity'. Forty-one different typical dwellings are used in order to determine a unique criterion for the acceptable air leakage under test conditions, which ensures an average of one air change per hour in most Israeli dwellings.

The second part of the paper demonstrates the energy inefficiency arising from using flueless appliances, when minimum health standards are required and translated into minimum constant ventilation requirements.

1. ENERGY SAVING

1.1 *Introduction*

THE VOLUMETRIC heat loss parameter G, for steady-state energy calculations, consists of the sum of two partial parameters:

- G_f—the partial value due to heat flow across walls, windows and exterior floor or ceiling elements, and
- G_N—the partial value due to heat removed by warm air leaking out of the dwelling and cold air leaking in, known as the 'air change' phenomenon.

Relating the average value of the volumetric heat loss parameter $\bar{G}$ to the total energy consumption E during one winter season by

$$E=\bar{G}\cdot\overline{\Delta T}\cdot V\cdot n \tag{1}$$

where $\overline{\Delta T}$ is the average difference between the interior design temperature (recommended minimum value for Israel: 18°C) and the exterior temperature, V is the net volume of the dwelling and n is the number of heating hours during the winter. It is possible to set design values to $\bar{G}$ for a typical dwelling (V) according to requests for energy saving (determination of E) and local climate ($\overline{\Delta T}$). This approach has been adopted in a proposal document for performance specifications for building elements[1] and by the Israeli Standard Committee for thermal insulation of dwellings.

Rewriting E using G_f and G_N and averaging over time, it is obtained

$$\begin{aligned}E&=\overline{(G_f+G_N)}\cdot\overline{\Delta T}\cdot V\cdot n\\&=(\bar{G}_f+\bar{G}_N)\cdot\overline{\Delta T}\cdot V\cdot n\\&=G_f\cdot\overline{\Delta T}\cdot V\cdot n+0.3\bar{N}\cdot\overline{\Delta T}\cdot V\cdot n\end{aligned} \tag{2}$$

where $\bar{N}$ is defined as the average value of the air change per hour during the winter and $0.3(\mathrm{Wm^{-3}\,1°C^{-1}})$ is the volumetric specific heat of the air.

Analysis of the partial influence of the various factors involved in the computation of $\bar{G}$ shows that an average value of $\bar{N}=1/3$–2 per h may be considered when 'reasonable design' is the approach (this implies that only less than 30% of the energy consumption stems from air change), and the most recommended value is $\bar{N}=1.0$ per h.

Assessment of $\bar{N}$ at the design state is thus necessary whenever design for 'energy saving' is performed.

Using the preceding approach we outline in the sequel the various parameters influencing the value of $\bar{N}$, and the method of determining their design measures.

1.2 *Air change mechanism*

The dwelling is represented by its net volume V and it is assumed, for simplicity, that all external openings are closed by the same type of windows with a characteristic air flow parameter γ, so that[2]

$$u=\gamma\sqrt{\Delta p} \tag{3}$$

where u is the volume of air leaking through the windows per unit crack length per second ($\mathrm{m^3m^{-1}s^{-1}}$) and Δp is the pressure difference across the window.

A further simplification is introduced by assuming that: (1) the exterior pressure is homogeneous outside

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of all the windows through which air is penetrating into the dwelling and denoted by $p_1(t)$. It may thus be represented by one coefficient C_1; 2. The same holds for the pressure outside of the leeside windows which is denoted by $p_2(t)$, thus being represented by another coefficient C_2. The interior pressure is represented by the time varying value of the excess pressure $p_3(t)$, so that the pressure difference across windows on the front side of the wind Δp_f is given by

$$\Delta p_f = p_1(t) - p_3(t) = \tfrac{1}{2}\rho[v(t)]^2 C_1 - p_3(t) \tag{4}$$

and across windows on the lee side Δp_l by

$$\Delta p_l = p_3(t) - p_2(t) = p_3(t) - \tfrac{1}{2}\rho[v(t)]^2 C_2 \tag{5}$$

where $v(t)$ is the wind velocity ($\mathrm{m\,s^{-1}}$) and ρ is the exterior air density under standard quiet conditions ($\mathrm{kg\,m^{-3}}$).

Applying the conservation of mass principle to the system it follows that

$$\frac{V\mathrm{d}\rho_3}{\mathrm{d}t} = \rho\gamma\left(L_1\sqrt{\tfrac{1}{2}\rho C_1 v^2 - p_3} - L_2\sqrt{p_3 - \tfrac{1}{2}\rho C_2 v^2}\right) \tag{6}$$

where L_1 and L_2 are the total window crack lengths on the front and lee side of the wind respectively (m), ρ_3 is the interior air density ($\mathrm{kg\,m^{-3}}$), and ρ_3, v and p_3 are time varying functions.

The actual process which occurs in the dwelling is neither adiabatic, nor isothermal. But, whenever there is a self-regulating heat source which keeps the interior air at a quite constant temperature, it is assumed that isothermal conditions prevail, thus use is made of the simple equation of state

$$P_3 = n_3 RT \tag{7}$$

where n_3 is the number of gram-moles of air in the volume V at time t, R is the gas constant and T is the absolute temperature.

Denoting by ρ_m the mass of a gram-mole of air it follows that

$$\rho_3 = \frac{n_3\rho_m}{V} = \frac{p_3\rho_m}{RT}. \tag{8}$$

But under quiet conditions (no wind) it holds that

$$\rho = p_{\mathrm{at}}\frac{\rho_m}{RT} \tag{9}$$

where p_{at} is the atmospheric air pressure.

It follows then, by substitution into equation (6), that the governing equation of the air-change mechanism is given by

$$\frac{\mathrm{d}p_3}{\mathrm{d}t} = p_{\mathrm{at}}\frac{\gamma}{V}\left(L_1\sqrt{\tfrac{1}{2}\rho C_1 v^2 - p_3} - L_2\sqrt{p_3 - \tfrac{1}{2}\rho C_2 v^2}\right). \tag{10}$$

By definition the 'air-change' is the amount of air entering into the dwelling per unit time divided by the volume of the dwelling. Under dynamic conditions we define the 'entering air-change' as above and denote it by $N_1(t)$ and the 'escaping air change' by a similar definition with respect to the amount of escaping air and denote it by $N_2(t)$.

Equation (10) is integrated by means of a self-checking iteration scheme (see appendix). Solutions have been obtained for a few particular cases of wind velocity functions. The dwelling represented is known as type 12/72 of the Ministry of Housing of Israel, and its geometrical parameters are: $V = 128.8\,m^3$, $L_1 = 20.2\,m$, $L_2 = 17.8\,m$, $C_1 = 0.8$, $C_2 = -0.3$.

Two particular cases are analyzed: (1) An abrupt change in wind velocity

$$v(t) = v_0 + v_1 H(t) \tag{11}$$

where $H(t)$ is the Heaviside function ($H(t) = 0$ for $t \leqq 0$, $H(t) = 1$ for $t > 0$).

For large values of t the solution is given by the steady state solution for a constant wind of velocity $v_0 + v_1$. The numerical integration of equation (10) includes the transient part, and exhibits the built-up time of the interior pressure.

Varying γ between 'highly air tight' values ($\gamma = 0.0005\,\mathrm{m^4/\sqrt{kgm}}$) and 'poorly air tight' values ($\gamma = 0.002\,\mathrm{m^4/\sqrt{kgm}}$) it is observed that the built-up time is of the order of 0.2–1.5 s (see Fig. 1 for the case: $v_0 = 1\,\mathrm{m\,s^{-1}}$, $v_1 = 3\,\mathrm{m\,s^{-1}}$). A monotonous trend of increasing built-up time with decreasing γ is observed.

For a given value of γ and varying the values of $v_1 - v_0$ the same order of magnitude of build-up time is evident (see Fig. 2 for the case: $v_0 = 1\,\mathrm{m\,s^{-1}}$, $\gamma = 0.001\,\mathrm{m^4/\sqrt{kgm}}$) with the trend of increasing build-up time with increasing $v_1 - v_0$.

It is thus concluded that, for all practical cases, it may be assumed that the quasi-static (steady-state) response prevails whenever the characteristic time associated with changes in the wind velocity is of the order of 2 s or more.

In order to validate this assumption the second case is presented: (2) The wind velocity is given by the harmonic function

$$v(t) = v_0 + v_1 \sin 2\pi\nu t \tag{12}$$

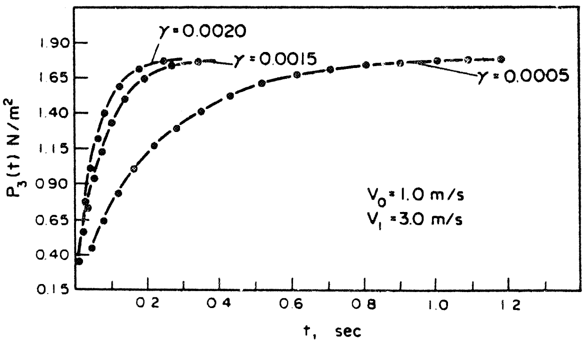

Fig. 1. Interior pressure response $p_3(t)$ to a step change in the wind velocity for various window air-tightness.

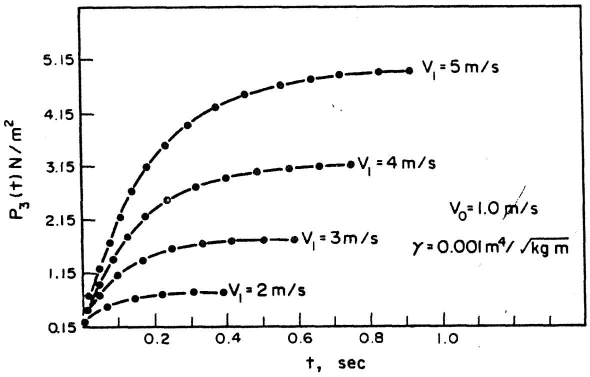

Fig. 2. Interior pressure response $p_3(t)$ to different step changes in the wind velocity for medium air-tight windows.

From the numerical solution it is observed that for low frequencies ($\nu < \frac{1}{4}$Hz) the solution is identical with the quasi-static response. For higher wind frequencies $p_3(t)$ does not build up to the quasi-static value (represented by pFIN3 in Figs 3 and 5) and a phase difference is observed. The smaller the value of γ, the stronger the build-up and the smaller the phase difference. Figures 3 and 4 represent the interior pressure p_3, the quasi-static interior pressure pFIN3, the 'entering air-change' N_1 and the 'escaping air-change' N_2, for $v_0 = 4\,\text{m}\,\text{s}^{-1}$, $v_1 - 1.0\,\text{m}\,\text{s}^{-1}$ and medium airtight windows with $\gamma = 0.001\,\text{m}^4/\sqrt{\text{kgm}}$. Figures 5 and 6 represent these functions for the same wind conditions but $\gamma = 0.0005\,\text{m}^4/\sqrt{\text{kgm}}$.

It is observed that the instantaneous entering 'air change' does not equal the escaping one, but the average values coincide and equal approximately the steady-state air change at the average wind velocity ($4.0\,\text{m}\,\text{sec}^{-1}$ in the case presented by Figs 4, 6). This represents a mechanism of an average 'cross ventilation' of the dwelling, which stems from the average wind velocity, with superimposed local fluctuations of air flow in the vicinity of the windows, which stem from the high frequency fluctuations in the wind velocity. These fluctuations contribute mainly to the unpleasant feeling when standing close to the window, but have a minor influence on the energy input, which is related mainly to the 'cross ventilation'. It is thus concluded, that from the point of view of energy consumption, the average air change computation may be based on the assumption that a quasi-static response to the average wind velocity prevails, thus

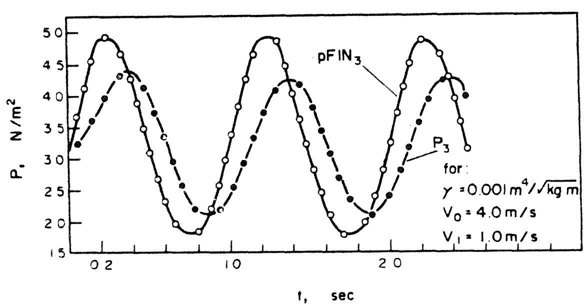

Fig. 3. Interior actual pressure response $p_3(t)$ and the quasi-static response pFIN3 to a harmonic wind velocity: medium air-tight windows.

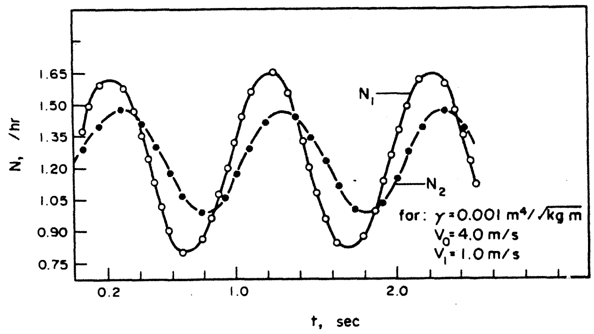

Fig. 4. The 'entering $N_1(t)$ and escaping $N_2(t)$ air changes' for a harmonic wind velocity: medium air-tight windows.

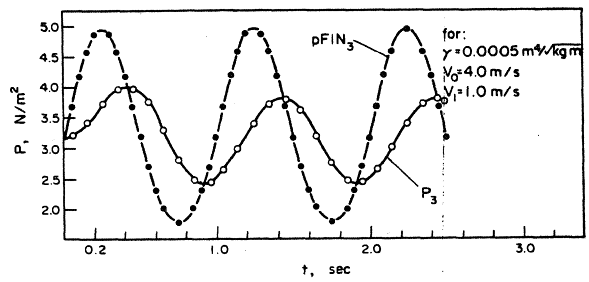

Fig. 5. Interior actual pressure response $p_3(t)$ and the quasi-static response pFIN3 to a harmonic wind velocity: highly air-tight windows.

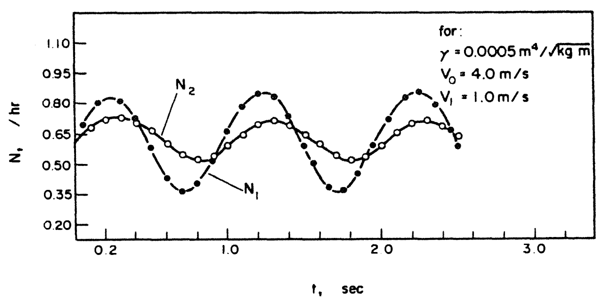

Fig. 6. The 'entering $N_1(t)$ and escaping $N_2(t)$ air changes' for a harmonic wind velocity: highly air-tight windows.

leading to an average internal pressure given approximately by

$$p_3(t) = \frac{L_1^2 C_1 + L_2^2 C_2}{L_1^2 + L_2^2} \tfrac{1}{2}\rho(\bar{v}(t))^2 = \tfrac{1}{2}\rho C_3(\bar{v}(t))^2 \quad (13)$$

where $\bar{v}(t)$ is the average wind velocity, which changes moderately with time (characteristic times larger than a few seconds).

This implies that the average entering and escaping air changes (per hour) are equal to each other and given by

$$N_1(t) = N_2(t) = N(t)$$

$$= \frac{3600 L_1 L_2 \gamma \sqrt{C_1 - C_2}\sqrt{\frac{1}{2}\rho}}{V\sqrt{L_1^2 + L_2^2}} \bar{v}(t). \quad (14)$$

Since meteorological data of wind velocity is obtained from field measurements only, transformation into the built region is required. Use may be made of Davenport's formula[3–8], thus leading to the wind velocity being given by

$$\bar{v}(t)=\bar{v}_{10}(t)\,27.5^{0.16}\left(\frac{Z}{Z_g}\right)\psi \tag{15}$$

where Z is the representative height for the region (10 m—for low to medium rise housing, 2/3 of building height for high rise buildings), Z_g and ψ—are given by Davenport for various types of regions and $\bar{v}_{10}(t)$ is the wind velocity at 10 m above ground in the free field (all high frequencies filtered out).

Introducing equation (15) into (14) and denoting by α

$$\alpha=27.5^{0.16}\left(\frac{Z}{Z_g}\right)^{\psi}3600L_1L_2\gamma\frac{\sqrt{C_1-C_2}\sqrt{\frac{1}{2}\rho}}{V\sqrt{L_1^2+L_2^2}} \tag{16}$$

it follows that

$$N(t)=\alpha\bar{v}_{10}(t). \tag{17}$$

This equation represents, for each particular dwelling, a linear dependence of the instantaneous air change on the average wind velocity in the field.

1.3 *A method for determination of the design wind velocity*

Denoting the partial average energy input per hour which is due to the air change by $\bar{E}_N$ it follows from equation (2) that during n heating hours

$$E_N=n\bar{E}_N=0.3\bar{N}\overline{\Delta T}\,Vn \tag{18}$$

and $\overline{\Delta T}$ is obtained by

$$\overline{\Delta T}=T_i-\bar{T}_0 \tag{19}$$

where T_i is the desired interior temperature (suggested value 18°C) and $\bar{T}_0$ is the average exterior temperature of the heating hours.

The heat input during a short time dt (s) is given by

$$E_N(t)=0.3N(t)\Delta T(t)V\frac{\mathrm{d}t}{3600} \tag{20}$$

and by substitution of equation (17)

$$E_N(t)=0.3\alpha\bar{v}_{10}(t)\Delta T(t)V\frac{\mathrm{d}t}{3600} \tag{21}$$

Integration over the total heating time (n hours) and averaging per hour gives

$$\bar{E}_N=\frac{1}{n}\left[0.3\alpha V\int_0^n\bar{v}_{10}(t)\Delta T(t)\frac{\mathrm{d}t}{3600}\right]. \tag{22}$$

Equating this value with the one defined in equation (18) it follows that

$$\bar{N}=\frac{1}{\overline{\Delta T}}\alpha\frac{\int_0^n\bar{v}_{10}(t)\Delta T(t)\frac{\mathrm{d}t}{3600}}{n}. \tag{23}$$

The expression

$$v_{\text{av.}}=\frac{1}{n\overline{\Delta T}}\int_0^n\bar{v}_{10}(t)\Delta T(t)\frac{\mathrm{d}t}{3600} \tag{24}$$

is the weighted average of the wind velocity during the n heating hours, where the weighing function is the temperature difference $\Delta T(t)$.

(For simplification purposes, the integration may be transformed into the summation of products of 1-h averages, since $\Delta T(t)$ is almost constant during 1-h periods. $\bar{v}_{10}(t)$ is then identified with the average wind velocity per hour which is usually available from raw meteorological data.)

It follows that

$$\bar{N}=\alpha v_{\text{av.}} \tag{25}$$

i.e. the average 'air-change' $\bar{N}$ from the standpoint of average energy consumption per winter, may be derived from equation (25) where α is given by equation (16), and the average wind velocity is obtained by equation (24).

This method of averaging gives most emphasis to cold days with strong winds and least emphasis to warm days with light winds. However, if strong winds occur on warm days, or light winds on cold days, their influence is moderate.

Note that simple averaging of equation (17) leads to

$$\overline{N(t)}=\alpha\overline{\bar{v}_{10}(t)} \tag{26}$$

where $\overline{\bar{v}_{10}(t)}$ is the simple average of the wind velocity over time, but $\overline{N(t)}$ does not coincide with the definition of $\bar{N}$ in equation (2).

Three years' (winters only) data of the Ashdod station of Israel has been processed by both methods leading to the values in Table 1.

It is obvious that, for the region concerned, the stronger winds are associated with comparatively warmer days, thus leading to $v_{\text{av.}}$ being consistently lower than $\overline{\bar{v}_{10}(t)}$. However, the large standard deviation causes over-lapping of the 90% velocity domains and thus implies that, for practical purposes, both methods are equivalent.

We assume now that for any practical use, the average air change (however defined) is proportional to the design wind velocity v_d, with α being the proportionality factor.

A third possibility for establishing v_d is the use of accumulative occurrence of one hour average wind velocities. However, this method should be approached with some caution. If the meteorological station provides occurrence data of one hour averages of the whole day or evening, it may be used according to a 70% of occurrence criterion. If processed data is based on one hour per day averages only (as is the case in Israel) it is not recommended to assign the design wind velocity according to this value, but perform data processing according to one of the above methods. (In Table 1 is included the accumulative occurrence of the wind velocities of whole evenings according to the

Table 1. Wind velocities processing by three different methods (three years, data of the Ashdod Station of Israel).

									Accumulative occurrence data according to Bophor Scale											
									Quiet winds 0–5.49 km h^{-1}			Light winds 5.5–19.49 km h^{-1}			Moderate winds 19.5–38.49 km h^{-1}			Strong winds 38.5–61.49 km h^{-1}		
1-A	1-B	1-C	1-D	1-E	1-F	1-G	1-H	1-I	1-J	1-K	1-L	1-M	1-N	1-O	1-P	1-Q	1-R	1-S	1-T	1-U
Evening	East	40.7	13.8	2.74	11.4	3.83	9.9	2.84	—	—	—	94.1	10.7	2.98	5.9	21.3	1.55	—	—	—
17.00	South	35.2	13.0	2.07	15.0	6.74	14.4	6.74	1.1	5.0	—	82.1	12.7	3.22	15.7	25.8	5.79	1.1	41.0	—
to	West	18.2	15.7	2.02	26.2	9.67	25.1	9.17	—	—	—	28.9	15.0	2.51	60.0	28.4	5.09	11.1	43.8	3.19
24.00	North	5.9	13.6	1.87	15.5	8.81	14.4	9.38	—	—	—	80.0	11.8	3.77	20.0	30.3	7.25	—	—	—
Night 24.00 to 8.00	South-East	87.9	10.8	2.71	14.3	5.24	13.6	5.07	2.6	3.1	1.43	84.4	13.1	3.31	13.0	23.9	3.72	—	—	—

1-A —Part of day
1-B —Wind direction
1-C —Occurrence of direction (%)
1-D —Average temperature (°C)
1-E —Standard deviation (°C)
1-F —Regular average wind velocity (km h^{-1})
1-G —Standard deviation (km h^{-1})
1-H —Weighted average of wind velocity (km h^{-1})
1-I —Standard deviation (km h^{-1})
1-J —Occurrence (%)
1-K —Average velocity (km h^{-1})
1-L —Standard deviation (km h^{-1})
1-M—Occurrence (%)
1-N—Average velocity (km h^{-1})
1-O—Standard deviation (km h^{-1})
1-P —Occurrence (%)
1-Q—Average velocity (km h^{-1})
1-R —Standard deviation (km h^{-1})
1-S —Occurrence (%)
1-T —Average velocity (km h^{-1})
1-U —Standard deviation (km h^{-1})

Bophor Scale, it may be observed that discrepancy from $v_{av.}$ is comparatively large.)

1.4 *A method for the establishing of standard test acceptance criteria for window air tightness*

Standard window testing for air tightness is usually accomplished by specifying the pressure difference across the window Δp_{test} and the limit value of the volume of air leaking through per unit length per unit time u_{test}, so that under test conditions

$$u=\gamma\sqrt{\Delta p_{test}}\leqq u_{test}. \tag{27}$$

If the test is conducted under a pressure difference which coincides with the stagnation pressure of the design wind velocity, i.e.

$$\Delta p_{test}=\tfrac{1}{2}\rho\left[27.5^{0.16}\left(\frac{Z}{Z_g}\right)^{\psi}v_d\right]^2 \tag{28}$$

and a unique* limit value is assigned to u_{test}, it follows that the average air change, in a dwelling with standard type windows, is given by

$$\bar{N}=\frac{3600L_1L_2\sqrt{C_1-C_2}}{V\sqrt{L_1^2+L_2^2}}u_{test}. \tag{29}$$

Demanding now, that $\bar{N}=1.0$ per hour for as many dwellings as possible for which the design wind velocity is v_d, it follows that

$$u_{test}=\frac{V\sqrt{L_1^2+L_2^2}}{3600L_1L_2\sqrt{C_1-C_2}} \tag{30}$$

Equation (30) includes only geometric parameters. It enables establishing the unique test acceptance criterion u_{test} according to an average value, as computed from many dwelling types.

Using 41 different types of public housing dwellings (built in Israel by the Ministry of Housing during the last two decades), with a volume range of 71.28–216.74 m^3 and various window sizes (see Table 2) it was obtained for Israeli purposes.

$$u_{test}=10.7\pm1.8\ (\mathrm{m^3m^{-1}h^{-1}}) \tag{31}$$

i.e. if, under the pressure difference given by equation (28) the air leakage through the tested window does not exceed $10.7\pm1.8\,\mathrm{m^3m^{-1}h^{-1}}$, it may be assumed that, on the average throughout the winter, for most Israeli dwellings, in which these window types are used, it holds that $\bar{N}=1.0$ per hour, thus leading to a reasonable energy saving.

*This implies that test conditions differ only according to region and type of housing, but the acceptance criterion is unique.

Table 2. Data processing of 41 typical Israeli dwellings for the evaluation of u_{test} ($C_1=0.8$).

Dwelling type	Net volume V(m^3)	Length of cracks on wind front L_1(m)	Length of cracks on lee side L_2(m)	C_2	u_{test} (m^{3}m^{-1}h^{-1})
91/35	71.28	13.6	8.1	−0.2	10.24
61/37	79.60	15.6	8.3	−0.3	10.36
89/52	96.45	9.3	14.6	−0.4	11.22
61/52	100.25	11.7	18.2	−0.4	9.30
14/55	100.80	11.8	22.0	−0.3	9.24
25/59	113.13	15.8	12.1	−0.3	11.23
61/58	113.68	11.8	23.7	−0.4	9.82
61/58	113.68	18.0	17.5	−0.4	8.27
07/70	124.08	13.2	22.2	−0.3	10.43
12/72	128.80	20.2	17.8	−0.3	9.20
91/56	129.81	13.8	20.0	−0.37	10.57
61/71	130.30	15.7	22.7	−0.4	9.21
85/72	130.30	13.6	21.6	−0.4	10.34
61/70	130.93	15.5	19.8	−0.4	9.79
15/66	132.55	11.2	25.2	−0.35	12.64
89/70	133.88	9.3	25.5	−0.33	15.10
89/70	133.88	9.3	21.9	−0.4	14.28
12/74	135.32	18.8	20.6	−0.33	9.60
85/74	135.88	20.9	21.0	−0.4	8.37
12/72	139.85	11.0	21.2	−0.35	13.98
85/72	140.78	13.7	25.4	−0.4	10.66
85/73	143.25	13.7	29.0	−0.4	10.56
61/75	143.43	15.4	22.0	−0.4	10.38
35/73	143.80	19.4	12.3	−0.3	13.20
61/74	145.63	16.0	24.0	−0.4	9.99
44/75	148.93	25.2	15.4	−0.3	10.81
41/81	153.10	25.6	18.7	−0.3	9.67
61/76	157.80	15.8	29.0	−0.4	10.38
61/76	157.80	23.0	21.8	−0.4	9.10
61/76	157.93	18.7	25.9	−0.4	9.51
61/76	157.93	20.1	24.5	−0.4	9.28
47/88	169.18	19.6	13.6	−0.3	14.44
85/89	170.65	20.9	17.6	−0.4	11.57
12/89	171.00	16.8	25.0	−0.33	12.08
62/92	174.00	22.1	33.4	−0.4	8.62
62/92	174.00	28.2	27.3	−0.4	8.10
85/90	178.35	13.6	23.3	−0.4	13.86
44/90	179.08	22.3	32.0	−0.3	9.33
89/90	182.43	22.7	23.0	−0.35	11.02
85/92	187.63	17.7	23.9	−0.4	12.04
04/93	216.74	23.0	27.8	−0.3	11.66

Average value of $u_{test}=10.72\,\mathrm{m^3m^{-1}h^{-1}}$.
Standard deviation of this value $=1.78\,\mathrm{m^3m^{-1}h^{-1}}$.

2. REQUIRED MINIMUM VENTILATION

2.1 *Introduction*

The demand for energy saving led the author to establishing the standard test conditions and criterion from an 'averaging over time' point of view. The air tightness of the dwelling thus achieved may be assumed a 'proper' one when the heating appliances do not add poisonous gases into the dwelling. Since in Israel the most customary means of heating are still the flueless gas and kerosine appliances, it is necessary to establish the criteria for required constant ventilation.

The harmful gases which are considered here are: CO_2, CO, SO_2 and cooking gas (due to leakage).

The Israeli kerosine includes 87% C, 13% H and 0.2% S (weight percentage), and the cooking gas includes 83% C and 17% H.

Standard regulations[9, 10] limit the emitted volume of CO to 2% of the emitted CO_2. It thus follows that per 1.0 KW the emitted amounts of the poisonous gases S_1 are as given in Table 3.

Table 3. The emitted amounts of poisonous gases S_1 per 1.0 KW heating of a flueless appliance.

Fuel type	Type of gas	Volume of emitted gas $(m^3h^{-1}) \cdot 10^{-3}$
Cooking gas	CO_2	145
	CO	3
	SO_2	—
	Leaking gas	100*
Kerosine	CO_2	170
	CO	3.5
	SO_2	0.15

*This amount is actually not related to the 1 KW and is thus constant for any heating input. It stems from the lowest opening position of a conventional gas range.

The hazards of the various gases have been discussed by physicians[11, 12] and the available data today enables the establishing of limit criteria to maximum concentrations permitted in closed spaces.

The values recommended for housing by the author, which are based on a literature survey[13–16] are given in Table 4.

Table 4. Maximum permitted concentrations ϕ_{max} of poisonous gases in a dwelling.

Type of gas	Concentration ϕ_{max} (per volume)
CO_2	0.5%
CO	30 ppm
SO_2	5 ppm
Cooking gas	1%

2.2 *Required minimum ventilation*

Assuming a steady-state system with an initial concentration of the poisonous gas equal to its value in the exterior, it follows (from the conservation of mass principle) that

$$\phi_i = \frac{S}{NV} e^{-Nt} + \phi_0 + \frac{S}{NV} \tag{32}$$

where ϕ_i, ϕ_0 are the interior and exterior concentrations of the gas, N is a constant air change and S is the amount of emitted gas from internal sources. Since the first term decays after a short time (decreases by 90% after $2.3/N$ h) in the sequence of a whole evening and night, it may be assumed that the interior concentration actually reaches the value at $t \to \infty$, i.e.

$$\phi_i \simeq \phi_\infty = \phi_0 + \frac{S}{NV}. \tag{33}$$

Equating this value with the maximum allowable concentration ϕ_{max}, it follows that the required minimum constant ventilation per hour is given by

$$N_{min} = \frac{S}{V(\phi_{max} - \phi_0)} = \frac{S_1 E_1}{V(\phi_{max} - \phi_0)} \tag{34}$$

where E_1 is the energy input per hour.

The amounts of fresh air required per 1.0 KW q_1 are given in Table 5.

Table 5. Minimum amount of fresh air q_1 required per 1.0 KW (m^3h^{-1}).

	According to:			
Type of fuel	CO_2	CO	SO_2	Leakage*
Cooking gas	32	100	—	10
Kerosine	38	117	33	—

*Independent of the heating capacity.

For a given flueless appliance with a heating capacity of E_1 the required minimum constant ventilation per hour is thus given by

$$N_{min} = \frac{E_1 q_1}{V}. \tag{35}$$

2.3 *'Inefficiency index' of flueless appliances*

The requirement of a constant minimum ventilation imposes an extra energy load on the heating system if the same interior temperature is to be preserved. Denoting the average energy required per hour in order to maintain temperature difference Δt by E_{r1} (KW) it follows that

$$10^3 E_{r1} = V\overline{\Delta T}\left(G_f + 0.3\frac{q_1 E_{r1}}{V}\right) \tag{36}$$

and, after solution, the required energy E_{r1} is given by

$$E_{r1} = \frac{\overline{\Delta T}\, V}{10^3 - 0.3\overline{\Delta T}\, q_1} G_f \tag{37}$$

and the required minimum ventilation

$$N_{min} = \frac{q_1 \overline{\Delta T}}{10^{-3} - 0.3\overline{\Delta T} q_1} G_f \tag{38}$$

Assuming the ideal conditions that minimum ventilation is regulated so that under all circumstances N_{min} is provided but not exceeded, it follows that: the difference between energy input required from a flueless appliance and that required from a non-poisonous heating system, in order to maintain the same interior temperature is given by

$$\Delta E = E_{r1} - 10^3(V\overline{\Delta T}\, G_f + 0.3\, V\overline{\Delta T}) \tag{39}$$

where it is assumed that in the second case $\bar{N} = 1.0$ per hour is unavoidable.

The inefficiency index ν of the flueless appliance is defined by

$$\nu = \frac{\Delta E}{10^3 V\overline{\Delta T}(G_f + 0.3)}$$
$$= \frac{G_f}{10^3(G_f + 0.3)(10^3 - 0.3\overline{\Delta T}\, q_1)} - 1. \tag{40}$$

Figure 7 presents the variation of the inefficiency index v versus the volumetric heat loss due to heat flow through the external envelope G_f when the temperature difference $\overline{\Delta T}$ is 10°C. It is clear that, unless $G_f \leqq 0.56\,\mathrm{Wm^{-3}1°C^{-1}}$ for kerosine appliances and $G_f \leqq 0.7\,\mathrm{Wm^{-3}1°C^{-1}}$ for gas appliances, the minimum required constant ventilation exceeds $N = 1.0$ per hour and the inefficiency index is increasing with G_f. Note that for 'relatively well thermally insulated' dwellings ($G_f \simeq 1.0\,\mathrm{Wm^{-3}1°C^{-1}}$) the inefficiency index has already relatively high values (10% for gas and 20% for kerosine).

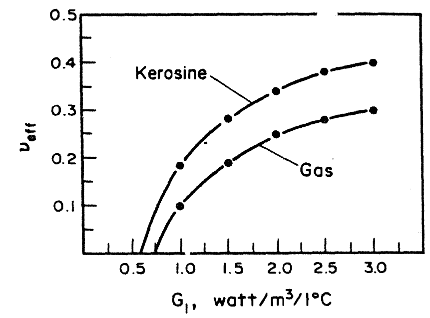

Fig. 7. Energy inefficiency of flueless appliances due to required constant ventilation.

3. CONCLUSION

It is demonstrated that ensuring a reasonable national energy saving per winter, by limiting the average air change to one per hour in most dwellings, is enabled by establishing well defined test conditions. The pressure difference across the tested window is related to the meteorological field data for wind velocity and it is shown that a weighted average is a best approximation for the design velocity, but actual data processing of one station exhibits that regular averaging may be used as well. Varying the pressure difference according to country region, type of urban area and category of building (high, low, etc.) enables the use of a unique limit value to the acceptable leakage ($\mathrm{m^3 m^{-1} h^{-1}}$) under the test conditions. The value has been established for Israeli public housing according to 41 different, typical dwellings and shown to be $10.7 \pm 1.8\,\mathrm{m^3 m^{-1} h^{-1}}$.

Using windows which passed these test conditions would ensure, in most Israeli dwellings, an average air change of one per hour. It is, however, warned that where flueless appliances are used, minimum health conditions require a constant ventilation which depends on the energy input. It is shown that this requirement may be very large when the dwelling is poorly insulated and a reasonable interior temperature is maintained by a high capacity appliance, e.g. for a dwelling with a volumetric heat loss of 1.5 ($\mathrm{Wm^{-3}1°C^{-1}}$) through the external envelope heating by a kerosine appliance requires 28% more energy input (in order to maintain 10°C difference between internal and external temperature) than heating by a non-poisonous heating system and an average air change of one per hour. A general inefficiency index is defined and may serve for economic evaluations and comparisons of various heating methods.

APPENDIX—NUMERICAL INTEGRATION PROCEDURE FOR THE SOLUTION OF THE FLOW EQUATION

The flow equation (10) is a nonlinear differential equation. It may be represented schematically by

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \mathrm{sign}\,(E_2 - y)E_1\sqrt{|E_2 - y|} - \mathrm{sign}\,(y - E_4)E_3\sqrt{(y - E_4)} \quad y(0) = E_5 v_0^2 \qquad (\mathrm{A.1})$$

where E_1, E_3, E_5 are constants E_2, E_4 are functions of time, proportional to the square of the wind velocity $v(t)$.

Rewriting equation (A.1) as

$$\frac{\mathrm{d}y}{\mathrm{d}t} = f(y, t)$$

$$y(0) = y_0. \qquad (\mathrm{A.2})$$

It is evident that the Runge–Kuta integration procedure may serve for starting the integration.

Since this procedure is not numerically stable and does not contain an internal correction scheme, it is used only for the evaluation of the first iterative solution when progressing from t to $t + \Delta t$. Thus, denoting the correct solution at time t by $y(t)$, the first progressive iteration is accomplished by:

$$y_1(t + \Delta t) = y(t) + k \qquad (\mathrm{A.3})$$

where k is given by the Runge–Kuta procedure[17].

A self-checking and correction procedure is now used in order to obtain the correct value of $y(t + \Delta t)$. The procedure is as follows:

(1) $\mathrm{d}y/\mathrm{d}t|_{t+\Delta t}$ is computed from (A.2) using the value of $y_1(t + \Delta t)$ in $f(y_1, t + \Delta t)$.

(2) Using backwards finite differences (with unequal intervals) it is obtained that a better iteration of $y(t + \Delta t)$ is given by

$$y_2(t + \Delta t) = \Delta t_{-1}\Delta t(\Delta t_{-1} + \Delta t) f(y_1, t + \Delta t) + y(t)(\Delta t_{-1} + \Delta t)^2 - y(t - \Delta t_{-1})\Delta t_{-1}^2 / \Delta t_{-1}(2\Delta t + \Delta t_{-1})$$

where Δt_{-1} is the former time step.

(3) $y_2(t + \Delta t)$ is compared with $y_1(t + \Delta t)$. If $\mathrm{abs}\,(y_2(t + \Delta t) - y_1(t + \Delta t))/y_1(t + \Delta t)) \leqq \varepsilon$, where ε is as small as desired for precision's sake, convergence is achieved.

It is then declared that $y(t + \Delta t) = y_2(t + \Delta t)$ and progress is made to $y_1(t + \Delta t + \Delta t_{+1})$ using (A.3). If the absolute value above is larger than the specified value ε the value of $y_2(t + \Delta t)$ is assigned to $y_1(t + \Delta t)$ and the procedure is restarted from step 2 onwards, until convergence is obtained. (In order to avoid singularity in case that $y_1(t + \Delta t)$ is zero, the denominator is given the value $y(0)$ and ε is given the value 10^{-7}.)

(4) The above procedure is valid at every time step except the first one. The first iteration from $t = 0$ to

$\Delta t y_1(\Delta t)$, is accomplished using (A.3). Then step 2 follows as above. At step 3 a backwards polinom of rank 3 through $t=0$ and $t=\Delta t$ is used yielding

$$y_2(\Delta t)=\tfrac{1}{2}\Delta t(f(y_1,\Delta t)+f(y_0,0))+y_0. \qquad \text{(A.4)}$$

The other steps follow as above.

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