# Monitoring the Effects of Draught Elimination

F. Bloisi,* M. Grosso,† M. Matarazzo,‡ F. Passaro,‡ and L. Vicari*

* Institute of Physics, Faculty of Engineering, University of Naples, Naples (Italy)

† Faculty of Architecture, Politecnico di Torino, Turin (Italy)

‡ APRE SpA, Rome (Italy)

## SUMMARY

*A retrofit was carried out on a building of 36000 m³ volume. This eliminated air infiltrations around windows, using silicone caulking. The energy balance of the building was evaluated experimentally before and after the retrofit. Besides the useful experience gained through monitoring the thermal behaviour of the building, we verified the impact of unwanted air infiltrations on a building's energy wastage. The analysis of experimental data allowed us to extend the results obtained from town houses by other authors to apartment buildings.*[1-3]

## NOMENCLATURE

| | |
|---|---|
| $A$ | Area of the windows ($m^2$). |
| $c_w$ | Specific heat of water (J/kg). |
| $C$ | Thermal capacity of the building (J/K). |
| $E$ | Energy waste (J). |
| $E_F$ | Free energy (J). |
| $K$ | Thermal conductance ($=1/R$) of the building envelope (W/K). |
| $p_w$ | Water flow-rate ($m^3/s$). |
| $P$ | Atmospheric pressure (pa). |
| $\Delta P$ | Total pressure difference (pa). |



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| | | |
|---|---|---|
| $\Delta P_0$ | Total pressure difference with respect to the reference value (100 pa) (pa). |
| $\Delta P_c$ | Pressure difference (buoyancy) (pa). |
| $\Delta P_v$ | Pressure difference (wind) (pa). |
| $q_0$ | Air exchange per unit area, at reference pressure difference ($m^3/h\,m^2$). |
| $Q$ | Air exchange ($m^3/s$). |
| $Q_I$ | Increase of air exchange ($m^3/s$). |
| $R$ | Thermal resistance of the building envelope (K/W). |
| $\Delta t$ | Time interval (s). |
| $T_e$ | External air temperature (K). |
| $T_i$ | Internal air temperature (K). |
| $T_r$ | Temperature of water from the radiators (K). |
| $T_s$ | Temperature of the water to the radiators (K). |
| $v$ | Wind speed (m/s). |
| $W$ | Thermal power delivered (W). |
| $\langle x \rangle$ | Mean value of $x$. |
| $\Delta x$ | $= x_a - x_b$. The $\Delta$ abbreviation has also been applied to other symbols to indicate an increment of that parameter, e.g. $\Delta \tau$. |
| $y$ | Distance from the neutral point (m). |
| $\eta$ | Plant efficiency. |
| $\rho_a$ | Air density ($kg/m^3$). |
| $\rho_w$ | Water density ($kg/m^3$). |
| $\tau$ | Building time constant ($= RC$) (s). |

*Subscripts*

| | |
|---|---|
| a | After retrofit. |
| b | Before retrofit. |

## INTRODUCTION

In recent literature, experimental data can be found concerning the elimination of unwanted air changes through cracks[4,5] in town houses or fairly small buildings. In fact, the usual way to monitor air changes based on the diffusion of tracer gases, needs diffusers and measuring instruments located in almost every room. Apart from this, measurements require too much time.

Owing to the preponderance of apartment buildings and their energetic relevance in Italy, we decided to study the effect of unwanted air changes on one of them. We expected the effect to be a lot less than that detected in town houses, owing to the different surface-to-volume ratio and to the partition of the internal air. However the difference is amplified by the fact that the considered building is quite tall.

To obtain quantitative information about the effect, we chose a building (a school) of 36 000 $m^3$ volume, located in Turin and eliminated its draughts, mainly around windows, by the use of silicon caulking. We measured the total thermal exchange factor of the building before and after the retrofit and detected a reduction of about 20% in the rate of energy dissipation.

## THE BUILDING

In Fig. 1 we show the plan of the building chosen for this experiment. In Table I the fundamental structural characteristics of the building are described. We sealed the cracks around about 2500 $m^2$ of windows.

The original leakage rate was very high. Our instrumentation consisted of a big plastic bag fixed all around each of the windows. Air was then supplied to the bag and the air supply rate was revealed as a function of the difference of the pressures of the air in the bag and outside the building. Because the leakage area of the windows was high, we were not able to get an appreciable difference of pressure.

However, we tested our instruments in the laboratory and saw that they were able to measure an air infiltration rate per unit area of 0·022 m/s ($= 80\,m^3/h\,m^2$), computed at a pressure difference of 100 pa, so we knew that the rate of infiltration of the building was higher than this. In our

TABLE I
Fundamental Features of the Building

| | |
|---|---|
| Volume | 36 000 $m^3$ |
| Floors | 3 + ground floor |
| Floor height | 4 m<br>5 m (ground floor) |
| Total height | 17 m |
| Area of windows | 2 500 $m^2$ |

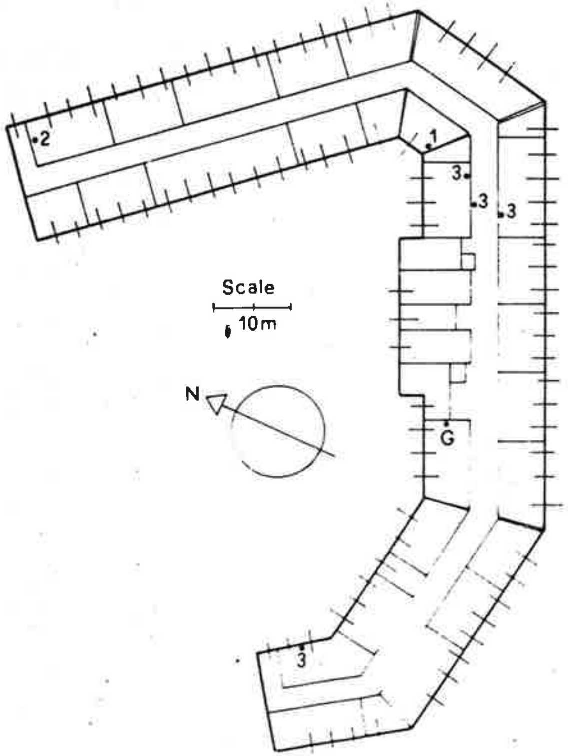


**Fig. 1.** Plan of the building: the positions of the temperature sensors are shown (G = ground floor).

theoretical computations we assumed a value of 0·028 m/s ($= 100\,m^3/h\,m^2$) at 100 pa pressure difference.

We chose the city of Turin because it has a cold climate for Italy. We assumed an average air temperature of 6·7 °C and an average wind speed of 2 m/s.

## THE METHOD

To determine the energy savings due to the elimination of the draughts we used a simple model of the building: an electrical equivalent network consisting of a capacitor, a resistance and a current generator, that is an



*RC* circuit. This model presents several advantages that compensate for its evident crudeness.

Our method, applied when the school was unoccupied, was to overheat it until its internal average temperature attained a value of about 27·5 °C. Then we turned off the heating plant and waited for the internal temperature to drop back to its original value. During the whole process we measured the internal average temperature and the amount of energy delivered to the building. Apart from this we measured the meteorological parameters. We took care to lower the temperature at night in order to reduce the influence of solar gains on the measurements. We performed this process twice before the draughts were eliminated during the winter of 1980/81 and twice during the winter of 1981/82, after the retrofit.

The behaviour of the internal temperature can be simulated by a network formed by as many nodes as desired, each node consisting of a capacitor and a resistance. The least number of nodes that must be used to fit all the data obtained, within the limit of the experimental errors, is two. We did not adopt this model because it requires the determination of four parameters instead of two. It must be observed that there are many different sets of parameter values that fit the experimental data, so that a more complicated model would not result in a more accurate measurement of the effect.

We then decided to use a simple *RC* model, taking care to choose values that fit the final part of the temperature curve well. During the first part of the drop in temperature we can assume that the temperatures of the internal air and internal structures are quite different. Some hours after the heating plant was turned off, we can assume a quite uniform internal temperature.

The first part of the experiment (i.e. with the temperature increasing) was less accurate than the second (i.e. with the temperature decreasing). During the diurnal heating of the building we needed to take the addition of solar energy into account.

We need the first part of the curve in order to determine *R* and *C* separately. We can calculate $\tau$, the *RC* product, by the last part of the curve. Because we are interested only in the percentage variation of the exchange factor, assuming that the internal capacity of the building does not change, we can use

$$\frac{\Delta R}{R_b} = \frac{R_a - R_b}{R_b} = \frac{\tau_a - \tau_b}{\tau_b}$$

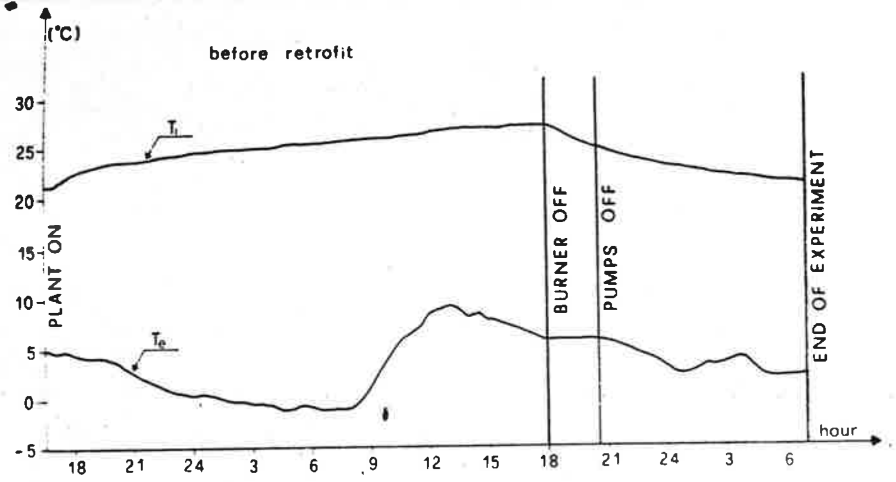


**Fig. 2.** Internal and external temperatures before the retrofit.

where 'a' means after and 'b' before the retrofit. We use the first part of the curve only to verify the assumption of the invariance of $C$.

In Figs 2 and 3 we present the internal average temperatures of the building as recorded before and after the elimination of draughts. The results of the application of the method under discussion are shown in Table 2. The inaccuracy of these results is about 10%.

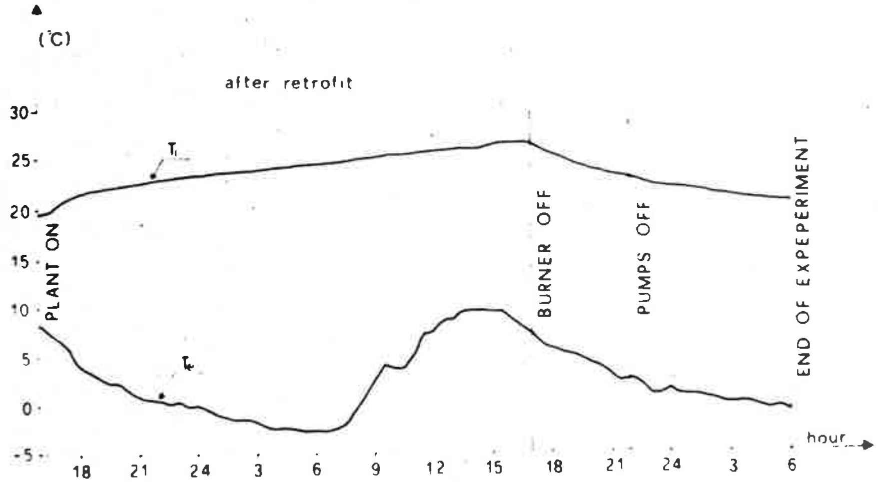


**Fig. 3.** Internal and external air temperatures after the retrofit

**TABLE 2**
Thermal Characteristics of the Building Before and After Its Retrofit

| | *Time constant* | *Heat capacity* | *Thermal resistance* ($R$) |
|---|---|---|---|
| Before retrofit | 190·8 s (53 h) | $5{\cdot}61 \times 10^9$ J/K ($1{\cdot}34 \times 10^6$ kcal/°C) | $34{\cdot}1 \times 10^6$ K/W ($39{\cdot}5 \times 10^{-6}$ h°C/kcal) |
| After retrofit | 277·2 s (77 h) | $5{\cdot}86 \times 10^9$ J/K ($1{\cdot}40 \times 10^6$ kcal/°C) | $47{\cdot}4 \times 10^{-6}$ K/W ($54{\cdot}9 \times 10^{-6}$ h°C/kcal) |
| Relative variation | 0·45 | 0·04 | 0·39 |

## THE EXPERIMENTAL APPARATUS AND THE MEASUREMENTS

The experiment required the measurement of several quantities such as meteorological parameters (including external ambient temperature, wind speed and orientation, and solar total radiations on horizontal surfaces) and system state parameters (heating plant turning on and off times, and temperature of the water entering the boilers). The measurement and the retrofit activities were also supported by infrared thermographic surveys revealing surface temperature distributions.

We will only describe in some detail the techniques used to measure the two most interesting quantities: the average internal temperature and the energy supply to the building.

To measure the average internal temperature we installed seven temperature sensors based on compensated thermistors with a maximum error of $\pm 0{\cdot}15$°C. Care was taken to set our sensors well away from windows, radiators and other sources of local variation in internal temperature. To avoid air stratification errors we set each of them at half the height of the rooms.

The thermal power delivered to the building was evaluated from the water inlet and outlet temperature difference and the flow-rate:

$$W = (T_s - T_r) p_w c_w \rho_w$$

The temperature difference $(T_s - T_r)$ was measured using a pair of compensated thermistors calibrated with an absolute error of $\pm 0{\cdot}2$°C. We measured the water flow-rate $p_w$ by means of a Woltman counter which had a relative precision of 2% in the range of values considered.

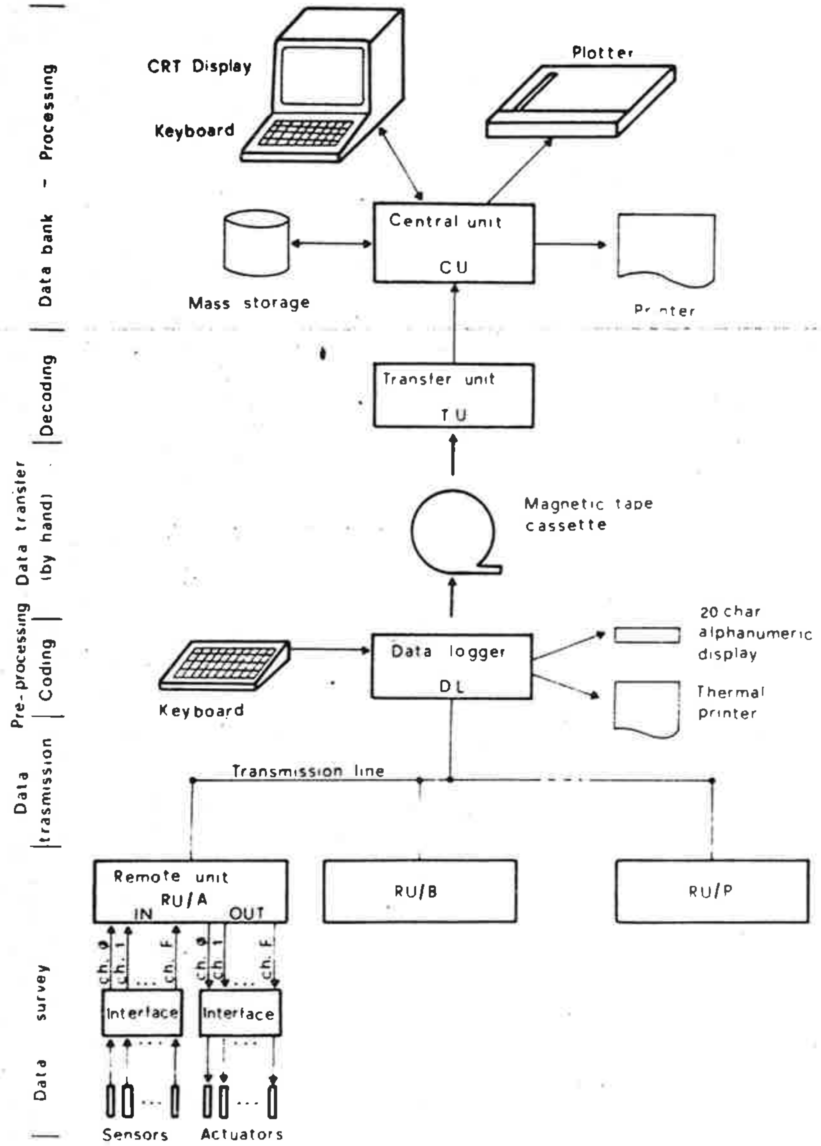


**Fig. 4.** Data logging and processing system.

The data were taken every 20 seconds, supplied to a microcomputer and elaborated. Their average values were recorded twice an hour on a magnetic tape. The magnetic tape was then fed to a computer where the data were preserved in a data bank. In Fig. 4 we show a scheme of the monitoring process.

## MODEL EFFECTIVENESS

We calculated the time constant of the building, taking into account the final part of the temperature fall (Fig. 5). In this figure, as in the following considerations, we chose the time origin $t = 0$ when the internal temperature of the building was 24 °C. This figure is very useful in order to gain a qualitative insight into the effect of eliminating draughts. The results show that the rate of temperature lowering after the retrofit is slower than before. This happened despite the external temperature being lower (average value 1·7 °C instead of 3·8 °C).

The fit of the experimental data is shown on log-linear graph paper in Figs 6 and 7. We select the initial time $t = 0$, corresponding to an internal

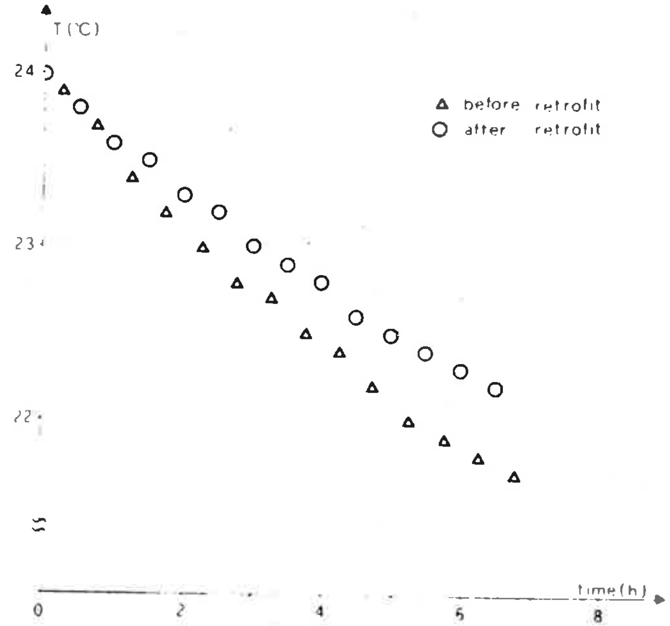


**Fig. 5.** Experimental data from which can be evaluated the building's time constant.

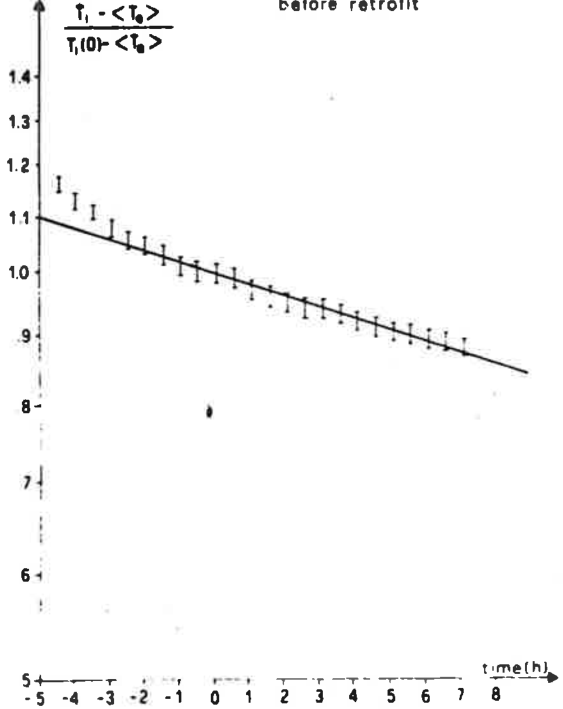


**Fig. 6.** Difference between internal and external air temperatures before the retrofit.

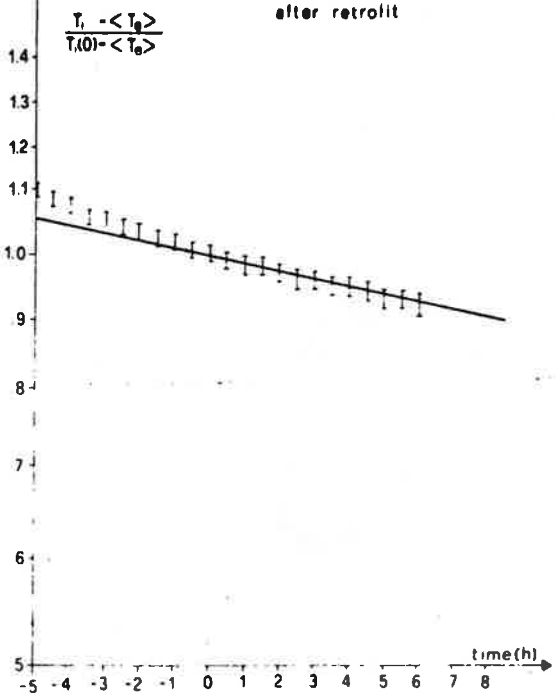


**Fig. 7.** Difference between internal and external air temperatures after the retrofit.

temperature of 24 °C. As expected, the fitting is only possible after the time $t = 0$.

The main error in our calculation is due to the neglect of part of the experimental data. To test the effect of this approximation, we extended our fit to this data and we observed their influence.

Until now, we have chosen, as the starting point of our computation, the time $t = 0$ corresponding to $T_i = 24$ °C. We now abandon this and use different values of the initial time $t'$ which is allowed to vary from the initial instant of the lowering of the internal temperature to the final part of our experiment. For every choice of $t'$, we again performed our calculations for the time constant $\tau$. The results are shown in Fig. 8.

As can be seen the calculated value of $\tau$ is affected by the choice for $t'$. This implies that our method is not reliable for this purpose. Nevertheless if we study the behaviour of $\Delta\tau (= \tau_a - \tau_b)$, we see that it is quite constant. This agrees with our hypothesis that $C$ is constant and that we have a definite variation of $\Delta R = R_a - R_b$.

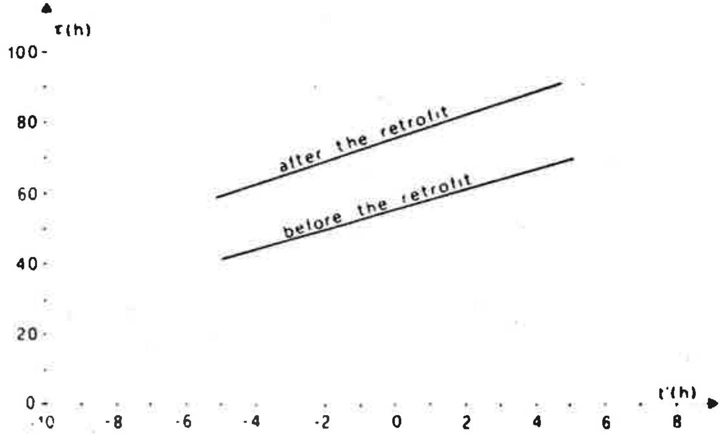


**Fig. 8.** Time constant versus starting time of experimental data.

Nevertheless $\Delta\tau$ also shows some dependence on the choice of $t'$. We can use this variation to estimate the order of magnitude of our error. From Fig. 8 we can see that $\Delta\tau$ ranges from the initial value of $86{\cdot}4 \times 10^3$ s (24 h), calculated taking into account only the last part of the curve, to a value of $72 \times 10^3$ s (20 h), with a total variation of 20%. We infer from these considerations that our method for the computation of $R_h$ incurs an error of $\pm 10$%.

## USUAL CONDITION CONSUMPTION

Even though the experiment has been carried out in particular thermal conditions, it is possible to extend its validity to more general conditions.

When we discussed the method, we introduced the total resistance of the building in the conventional way, that is:

$$R = \frac{\langle T_i \rangle - \langle T_e \rangle}{E} \quad \Delta t$$

where $E$ is the energy waste of the building during the time interval $\Delta t$.

It is well known that the value of $R$ is not a constant. Also, even if we disregard the radiative effects, we must take into account the dependence of the rate of air exchanges on the temperature difference $(T_i - T_e)$ Similarly $R$ is influenced by the wind.

In our previous considerations, we considered the values of the total thermal resistance as computed during the measurements, namely with $T_i(0) = 24\,°C$, $\langle T_e \rangle = 2\,°C$ and the wind speed = 1 m s. If we want to determine $R$ during an arbitrary time range, we need an expression that takes into account the dependence of the air changes on the meteorological parameters and the internal conditions. To do this, we use the expression introduced by Cali and Fracastoro:[6]

$$Q = Aq_0 \left( \frac{\Delta P}{\Delta P_0} \right)^{\gamma}$$

where

$$\Delta P = \Delta P_v + \Delta P_c$$

$$\Delta P_v = \tfrac{1}{2} v^2 \rho_a \alpha_1$$

and

$$\Delta P_c(y) = \alpha_2 \rho_a y \left( \frac{1}{T_e} - \frac{1}{T_i} \right)$$

Using SI units (so that $T_e$ and $T_i$ are in K), the values of the constants are

$q_0$ = measured value of air exchange per unit area ($m^3/s\,m^2 = m/s$), at a total pressure difference $\Delta P_0 = 100$ pa

$\gamma = 0{\cdot}65$ (dimensionless)

$\alpha_1 = 0{\cdot}43$ (dimensionless)

$\alpha_2 = 0{\cdot}0342$ (K/m)

To evaluate energy savings we must take into account the conditions that prevail under normal circumstances. Therefore we considered the thermal differences between the normal and the measurement conditions. Another difference is that the building was empty when measurements were being taken. If the users are in the building, the minimum value of the air changes cannot be chosen arbitrarily but has to ensure the users' comfort. This condition was satisfied before the elimination of air draughts but not afterwards. Therefore we must observe that the users opened the windows in order to increase the exchange of air. In our case the computed effect of this increase is

$$Q_1 = 2\,m^3/s\ (= 72 \times 10^3\,m^3/h)$$

Because we had the data of the building energy consumption during the years 1979/80 and 1980/81, before the retrofit and for 1981/82, after the elimination of air draughts, we used our model for those years to test the validation. The same computation performed for the average year gives us the annual savings.

## CONCLUSIONS

We computed the fuel consumption of the building in average meteorological conditions in the presence and absence of the air draughts. To check the reliability of our method we performed the computation also with historical data.

We used for the free energy sources, $E_g$, during a year the value

$$E_g = 2{\cdot}18 \times 10^{12}\,J\ (= 5{\cdot}2 \times 10^8\,kcal)$$

corresponding to a temperature increment of 5 °C, a value that we inferred as being quite satisfactory for the city of Turin.

We measured the plant efficiency and obtained

$$\eta = 0{\cdot}75 \pm 0{\cdot}05$$

**TABLE 3**
Comparison between the Computed and Measured Consumption Data

| Year | *Computed consumption (litres of gas oil)* | *Measured consumption (litres of gas oil)* |
|---|---|---|
| 1979/80 (before retrofit) | 111 000 | 108 700 |
| 1980/81 (before retrofit) | 104 500 | 103 800 |
| 1981/82 (after retrofit) | 101 400 | 102 200 |
| Average year (before retrofit) | 146 400 | — |
| Average year (after retrofit) | 117 400 | — |

As can be seen in Table 3, the difference between the computed and measured consumption data is less than 3%. This excellent corroboration stems from the knowledge we have of the building. We do not generally expect the method to yield an error of less than 10%.

Another observation has to be made concerning the data computed with regard to the average year: the meteorological data refers to the airport, outside the city. This would enhance the effect, because the temperature in the city is usually higher than the former and the savings lower than those computed.

To be conservative we reduce our estimated savings by 25%. In these conditions we get a saving of about $21 \times 10^3 \pm 10\%$ litres of gas oil in a year as a result of draught elimination. The capital cost of the elimination of draughts was equivalent to almost 50 000 litres of gas oil. Therefore the pay-back time is approximately 2·5 years.

## REFERENCES


1. R. H. Socolow. The Twin Rivers Program on energy conservation in housing: highlights and conclusions. *Energy and Buildings*, **1** (1977), p. 207.
2. D. T. Harrje. Details of the first-round retrofits at Twin Rivers. *Energy and Buildings*, **1** (1977), p. 271.
3. F. W. Sinden. Wind, temperature and natural ventilation—theoretical considerations. *Energy and Buildings*, **1** (1977), p. 275.
4. N. Malik. Field studies dependence of air infiltration on outside temperature and wind. *Energy and Buildings*, **1** (1977), p. 281.
5. D. T. Harrje and R. A. Grot. Instrumentation for monitoring energy usage in buildings at Twin Rivers. *Energy and Buildings*, **1** (1977), p. 293.
6. M. Calì and G. V. Fracastoro. Proposta di metodo per il calcolo delle infiltrazioni d'aria in un edificio multipiano. [Air infiltration calculation in a multi-storey building. *La Termotecnica*, 35(2) (1981), p. 62.