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Energy Efficient Design of Industrial Buildings

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Eight factories have been monitored, two designed in compliance with current recommendations for thermal insulation (0.6 W m^{-2} °C^{-1}) *and air infiltration, and six designed with increased levels of thermal insulation* (0.35–0.45 W m^{-2} °C^{-1}) *and reduced levels of air infiltration. Design energy targets are presented for the standard and "better insulated" factories. Results for measured* U*-values and air infiltration rates are presented and related to standard and recommended values. In general the measured* U*-value heat loss was found to be higher and the measured air infiltration rates were found to be lower than recommended design values. These measured values were used to calculate revised design energy targets which were then compared to the original design targets and measured operational targets. Operational energy targets for the better insulated factories were found to lie within* 0.30 *and* 0.34 GJ m^{-2} yr^{-1}. *The possibility of a "mismatch" between traditional heating system design and the heating requirements of low energy factories is discussed.*

1. INTRODUCTION

AN ESTIMATED 6% of the U.K.'s annual energy consumption is used for heating industrial buildings [1]. This compares with 28% used in the domestic building sector and 6% used in each of the commercial and public building sectors. Although not as large as the domestic building sector, the heating of industrial buildings is significant in national terms though until recent years, in comparison with (and in proportion to) the domestic sector, relatively little research, development and demonstration effort had been spent on reducing industrial space heating energy costs. Reducing these costs is also important in terms of individual companies who are finding that escalating energy costs are contributing a greater proportion of their annual turnover. There is therefore the need to provide industry with factory buildings that are efficient in their use of energy.

This general requirement for energy efficiency in the heating of factories comes at a time when the profile of U.K. industry is changing. The traditional emphasis on heavy industry is shifting to light manufacturing and service industries, requiring different types of buildings, with different (generally improved) environments. An energy efficient design, in addition to saving energy costs, should also make it easier (and cheaper) to achieve good environmental conditions. People today expect to be comfortable in their place of work and are arguably more productive when in a comfortable and "healthy" environment. So, not only must factories be designed to be heated efficiently, they must also, now more than ever, be able to maintain good environmental conditions. This is a time of new (and often speculative) building in the industrial sector. It is therefore timely to promote energy efficiency and environmental comfort in the current design and construction of what will amount to a significant proportion of our future industrial building stock.

In 1981 the Joint Technical Committee of the U.K. Estate Agencies recognized the need for increased energy efficiency for the space heating of factories and proposed a set of new "low-energy" standards for their Advance (speculative) Factory Programmes [2]. *U*-values for walls and roofs were reduced from the current recommended values of 0.6 W m^{-2} °C^{-1} [3] to between 0.35 and 0.45 W m^{-2} °C^{-1}, and measures were taken to reduce air infiltration rates, the factories being predominantly naturally ventilated.

In order to test whether or not such new "low-energy" design targets could be achieved in practice a range of "better insulated" factories were designed and constructed by the Welsh Development Agency (WDA) and their energy performance was monitored during the heating season (October–April) in a project funded by the Department of Energy (BRECSU), the Development Agencies of the U.K. and British Gas. The overall aim of this monitoring project was to demonstrate energy savings in practice by firstly, investigating whether or not the predicted reduction in *U*-values and air infiltration rates could be achieved in practice and, secondly, measuring the operational energy targets over a heating season and comparing them with design energy targets. This paper presents the main findings of the monitoring project as follows.

Firstly, the monitoring project is described in general terms. Next, design energy targets are presented in relation to current standards and to the improved standards of the better insulated factories investigated. The results of measurement surveys of the installation of insulation, *U*-value heat loss and ventilation rates are pre-

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sented and the measured values are compared to the standard values used in design predictions. Results of measured operational space heating energy performance are presented and the operational targets are compared with the design targets (based on the measured *U*-values and air infiltration rates). Finally, factory heating system design and the production of thermal environmental conditions is discussed in general terms in relation to low-energy factories.

2. MONITORING LOW ENERGY FACTORIES

In order to test the "low energy" design standards proposed by the WDA, a monitoring project was carried out involving six advance (speculative) factories built to the new "better insulated" specifications together with two advance factories built to the current standards, for comparison purposes (details of design standards are presented in Section 3).

The specific objectives of the monitoring project were:

(i) To assess the standard of installation of insulation for the main wall and roof construction types, to measure the *U*-value performance and to compare design standards against those constructed.

(ii) To measure the air infiltration rates in standard and better insulated factories and to compare the results with design guidelines.

(iii) To measure the seasonal energy performance and to compare measured operational targets with standard design targets and revised design targets, as moderated by the construction, i.e. using the measured *U*-values and air infiltration rates [(i) and (ii) above].

Physical monitoring techniques adapted from earlier work in the domestic sector were used [4]. Two levels of monitoring (described in detail elsewhere [5]) were employed, namely:

(i) To measure *U*-value and air infiltration performance: this involved thermographic surveys, continuous measurement of wall and roof heat flux's, and ventilation surveys.

(ii) To measure energy use and thermal environmental conditions in operation: this involved the continuous monitoring on a half hour time base of energy performance parameters, i.e. heating system and electrical (process, lights, etc.) energy inputs to the space, internal air temperatures (at between 4 and 12 positions, depending on factory size), and external climate conditions.

The monitoring was carried out in the eight factories which were located on two sites, namely, Maesglas (Newport) and Dafen (Llanelli), during the 1983/4, 1984/5 and 1985/6 heating seasons. Details of the factories investigated are summarized in Table 1.

All the factories were intended to be occupied at the time of monitoring, and the monitoring was to be carried out over a complete heating season. However, two factories (units 4 and 8) became unoccupied for part (approximately 10% and 50% respectively) of the heating season, and so data was not available for the complete heating season. Also two factories (units 5 and 6) remained unoccupied for the whole heating season and in these factories heating patterns were simulated (for approximately 30% of the heating season). These problems with occupancy did not stop the main objectives of the project, i.e. concerned with the operational performance of the fabric, being acheved.

3. DESIGN HEATING TARGETS

Before the results of the monitoring project are considered, design energy targets are presented, relating to the range of factories being monitored. In 1979 the U.K. Building Regulations [3] introduced maximum *U*-values for factories of 0.6 W m^{-2} $°C^{-1}$ for walls and roofs together with a single glazing allowance of 15% and 20% for walls and roofs respectively. Prior to this there was no requirement under the Building Regulations for fabric insulation in factories, although the Insulation (Industrial Buildings) Act (1959) required factory roof *U*-values to be below 1.7 W m^{-2} $°C^{-1}$.

There has been no legislative attempt yet to control the design of air infiltration in naturally ventilated buildings. However, for the purpose of energy calculations the CIBSE recommend a range of infiltration rates for various factory types [6]. In the early 1980's the WDA, on behalf of the Estate Agencies of the U.K., produced a set of design standards for low energy factory design. As stated in the introduction, these new standards specified a reduction in wall and roof *U*-values from 0.6 W m^{-2} $°C^{-1}$ to between 0.35 and 0.45 W m^{-2} $°C^{-1}$, together with a reduction in air infiltration rates, achieved by better detailing and the use of high performance components, e.g. well sealed loading doors.

Design energy targets for factories designed to the current Building Regulation standards and also to the WDA improved standards are presented in Table 2 for three factory sizes, namely, 200, 900 and 1800 sq m floor area (sizes which compare with the Project factories). These targets are for design fabric heat loss only, and do not include heating system efficiency factors. These targets are stated for design and seasonal (degree day) fabric heat loss and will be used to compare with the measured data presented later, the purpose being to compare between design and operational heat loss targets.

4. FABRIC HEAT LOSS PERFORMANCE

Design energy heat loss targets are based on the predicted performance of the fabric, usually in terms of the "*U*-value" heat loss through the walls, roof, etc. together with the heat loss through air infiltration, normally taken as a constant air change rate. These are then combined to provide a design heat loss target (in the U.K. typically for an internal/external air temperature difference of 20°C) and a seasonal heat loss target (usually using a degree day type of calculation), as given in Table 2. A heating system efficiency factor would then be used to relate heat loss to fuel use.

Before measured operational targets can be related to design targets, the components of fabric heat loss, i.e. the *U*-values and the air infiltration rates must be assessed and values of the components as combined in a construction compared with those used in design predictions.

Table 1. Details of project factories

Unit	U-value (wall and roof) (W m^{-2} °C^{-1})	Floor area (sq. m)	Heating system
1 (d)	0.35	180	Unit warm air, on/off control*
2 (d)	0.35	180	Direct fired wall mounted, radiant plaques, on/off control
3 (d)	0.35	180	
4 (c)	0.7	230	
5 (c)	0.45	900	Radiant tubes, on/off control
6 (c)	0.45	900	
7 (c)	0.45	1800	Overhead medium pressure hot water radiant panels, modulating control
8 (c)	0.7	2300	

Construction: c—Cladding walls and roof, d—masonry diaphragm wall with cladding roof.
* Later changed to modulating control.

4.1. *Insulation and* U-*values*

The heat loss through the walls and roofs was investigated in two stages.

(i) A thermography survey was carried out to determine the standard to which the insulation was installed.

(ii) The heat flux through the walls and roof of each factory was measured on a half hourly time base as part of the continuous monitoring programme and from this the U-values were calculated.

4.1.1. *Thermography survey.* A thermography survey was carried out on all the factory types. The roofs in all the units were of an insulated cladding construction. The walls of the smaller "better insulated" units were of a masonry diaphragm construction containing insulation in the cavity. All other walls were of a steel cladding construction containing the appropriate thickness of glassfibre quilt insulation.

The survey generally revealed that for the smaller (180 sq. m) "better insulated" units the installation of insulation was to a good standard, with only minor defective areas in the roof (less than 1% in terms of area). However for the larger (900 sq. m) units the survey revealed more defective areas (the order of 5% in area) in the roof, and some (less than 1% in area) in the wall, and so the overall standard of installation of insulation for these units could only be termed average. The interpretation of standards of installation of insulation is based on a number of previous thermographic surveys carried out on factories and other building types [7].

In the case of all identified insulation defects, the cause of the defect was due to adjacent layers of insulation quilt not being properly butted together. This has been identified as a commonly occurring fault for a cladding construction [7], and it may not be appreciated by the construction team that although the defective areas are relatively small relative to the total surface area the heat loss through them is by comparison large, in the cases presented above by a factor of approximately eight times what it should be (i.e. a U-value of say 3.5 W m^{-2} °C^{-1} instead of 0.45 W m^{-2} °C^{-1}). This implies that for the 1 and 5% missing area of insulation in the wall and roof of units 5 and 6, there would be an increase in overall conductive heat loss through the wall and roof of about 7 and 34% respectively.

The survey also highlighted the poor insulation level of the roller shutter doors of the standard design factory compared to the insulated door (U-value—0.45 W m^{-2} °C^{-1}) of the better insulated factory [7, 8]. In the smaller terraced units a poorly insulated loading door can represent the order of 25% of the total fabric conductive heat loss compared to 3% for the better insulated equivalent.

4.1.2. U-*value measurements.* In a number of the monitored factories (refer to Table 3), covering the range of types of construction used in the project factories, the heat flux was measured in one position of the wall and roof, in order to determine the operational U-values. The positioning of the heat flux sensor was checked against the thermography survey so that defective areas were avoided. The heat flux sensor (TNO WS31) was inserted into the construction between the inner skin and the insulation, thus avoiding the problems of surface effects, etc. that are experienced when sensors are fixed to the internal surface.

The U-values were obtained by dividing the accumulative average of the heat flux by the internal/external air temperature difference [9]. This analysis was carried out for typically a four week period, after which a stable U-value was obtained. An example of the analysis is given in Fig. 1 for the wall of unit 7 [10]. Figure 1 shows the

Table 2. Design energy targets for standard (building regulations) and better insulated (WDA) factories, for design and seasonal heat loss

	Standard		Better insulated	
Floor area (sq. m)	Design (kW)*	Seasonal (GJ m^{-2}/yr^{-1})†	Design (kW)*	Seasonal (GJ m^{-2}/yr^{-1})†
200	18.9	0.65	10.0	0.35
900	68.4	0,49	50.0	0.37
1800	132.6	0.47	80.0	0.29

* Based on a design internal/external air temperature difference of 20°C.
† Based on 2231 degree days.

Table 3. Measured and design U-values for walls and roofs

	U-value ($W\ m^{-2}\ °C^{-1}$) measured* wall	roof	Design wall and roof
2	0.4	—	0.35
3	0.4	—	0.35
4	0.72	0.72	0.6
5	0.51	0.52	0.45
6	0.62	0.45	0.45
7	0.53	0.51	0.45

*There is a measurement error of +/−10% associated with the measured U-values.

accumulative U-value for the first week of the analysis and the dotted line in the figure shows the accumulative U-value at the end of the fourth week, there being little variation after the end of the first week. Table 3 summarizes all the measured U-values, together with the design values.

In the following (Section 5) estimation of operational energy targets, the floor U-values of the smaller units (1–4) were based on CIBSE recommended values [11]. However, for the larger units (5–8), where slab heat losses can be proportionally more significant, floor U-values were calculated using a finite element computer program [12]. This allowed for ground moisture and the fact that the factories were being heated for the first time during the project and the slab was warming up "from cold".

4.2. *Air infiltration and ventilation*

The factories were all designed for natural ventilation with roof ventilator fans providing additional summer ventilation. Natural ventilation is dependent on internal/external temperature differences (stack effect) and wind velocity providing the driving forces. The rate of air infiltration is determined by the degree of leakage in the fabric, i.e. cracks around the loading door, service entries, etc. The CIBSE guidelines provide recommended values of air infiltration rates for factories for the purpose of heat loss calculations [6], but there is little data available on actual rates achieved in practice, and on the scope for reductions.

Ventilation measurements were carried out in the smaller units (2 and 3) and the larger units (5 and 6) to determine what the basic infiltration rates were and to quantify the proportion of leakage through major components such as the loading door and roof ventilators. Two types of measurement techniques [13, 14] were used in the investigations, namely:

(i) Pressurization—to determine rates of air leakage for a constant internal/external pressure difference (usually 50 pa). Although this technique does not provide an absolute measure of the air infiltration rate it does give a useful comparative measure of air leakage, and it is relatively quick to carry out.

(ii) Tracer gas (constant concentration method)—to determine the air infiltration rates at normal pressure differences.

A combination of the two techniques were used, measuring the actual infiltration rates with tracer gas methods, and using pressurization methods to gain a comparison across factories [14].

The first set of ventilation measurements involved comparing the standard design small factory (unit 4) to the "better insulated" design small factory (unit 3). The investigation was concerned with the measurement of basic infiltration rates, assessing the contribution of the (closed) loading door, and also the contribution from opening roof ventilators. The results are summarized in Fig. 2.

The results showed a marked reduction in infiltration (57%) between the standard design and the better insulated design. The main contribution to the leakiness of the standard design was the loading door, which when sealed reduced the infiltration rate by 45%. In comparison, the well sealed loading door of the better insulated design factory accounted for only 9% of the infiltration rate. Opening ventilators accounted for 5% and 12% of the leakage in the standard design and better insulated design respectively. Overall the measured infiltration rate of the standard design factory (1.4 ac hr^{-1}) was greater

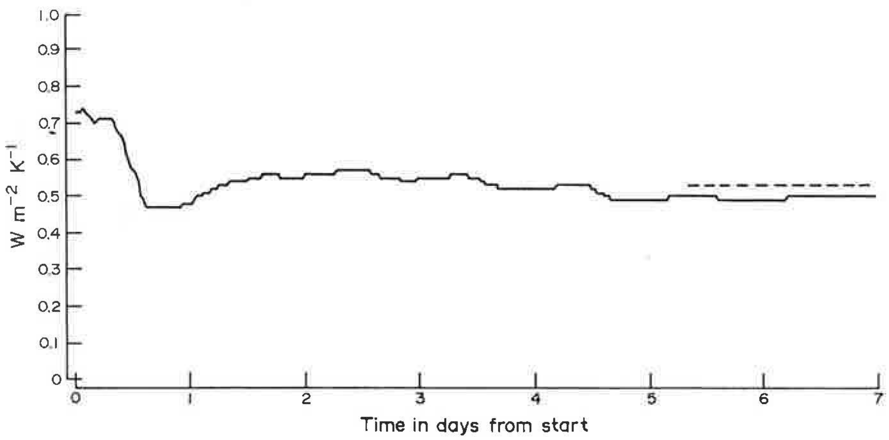

Fig. 1. Accumulative U-value over a seven day period for the wall of unit 7 from the start of analysis. The dotted line indicates the value at the end of the fourth week of analysis, which is the final value given in Table 3 [10].

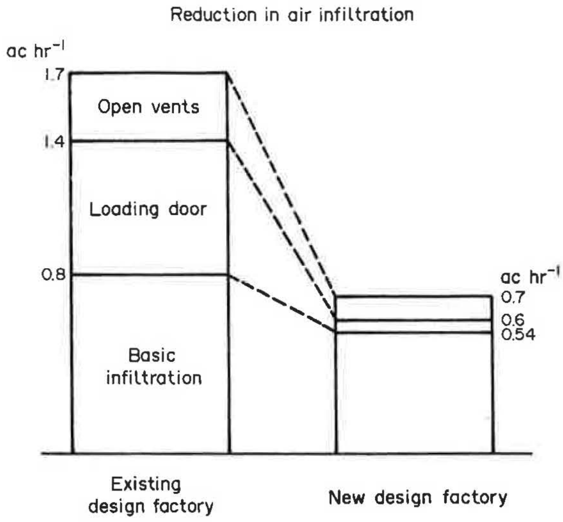

Fig. 2. Ventilation characteristics of unit 4 (existing design) and unit 3 (new design) showing the reduction in infiltration between units 4 and 3, the relative effects of leakage through the loading doors, and the effect of opening roof ventilators [12].

than the CIBSE recommended value (1.0 ac hr^{-1}) for the type of construction, while for the better insulated design factory the measured infiltration rate (0.6 ac hr^{-1}) was lower than the CIBSE recommended value (0.75 ac hr^{-1}) for the type of construction. Similar ventilation measurements were carried out in the two 900 sq. m factories (units 5 and 6) [10]. The average measured infiltration rate was found to be about 0.25 ac hr^{-1}, compared to the CIBSE recommended value of 0.75 ac hr^{-1}. Table 4 summarizes the air infiltration rate results.

In general, for the better insulated factories, the air infiltration rates measured in practice were lower than those suggested by the CIBSE guidelines for use in predicting heat loss. The uninsulated "leaky" loading door of the standard design factories (units 4 and 8) was identified as a major source of air leakage, and contributed to the measured infiltration rate of unit 4 being higher than the CIBSE recommended value.

4.3. *Summary of fabric heat loss performance*

—Missing insulation could result in an estimated increased heat loss of up to 7 and 33% for walls and roofs respectively for factories of cladding constructions.
—An uninsulated loading door could increase the overall conductive heat loss of a small unit by about 25%.
—Measured *U*-values compared with design *U*-values were generally within the range of experimental error, however on average the indication was that the measured *U*-values were of the order of 10% higher.

Table 4. Summary of measured and recommended air infiltration rates

Unit	CIBSE [8]	Measured (ac hr^{-2})*
2	0.75	0.6
3	1.0	1.4
5	0.75	0.25
6	0.75	0.25

* Estimated error of 12% [13].

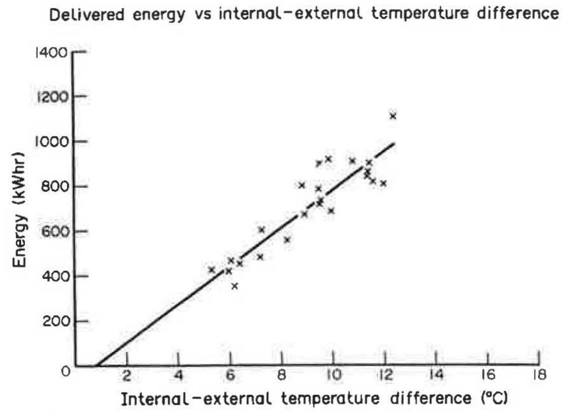

Fig. 3. Energy input to the production space of unit 2 plotted against the internal/external air temperature difference. The slope of the line represents the specific heat loss of the space [10].

—For the smaller units the measured air infiltration rates for the better insulated factories were generally lower than the CIBSE recommended values.
—In general the overall measured conductive losses tended to be higher than the design values, while the infiltration losses were lower.

5. OPERATIONAL ENERGY PERFORMANCE

The operational energy performance was defined as a measure of the energy a building uses under "normal" operation over a normal heating season.

To assess the energy performance of the factories, the weekly energy input to the space from both the heating system and the process load (where applicable) was plotted against the weekly internal/external air temperature difference. The calculated heat input to the space took account of the manufacturers stated efficiencies for the various heating systems (see Table 1). The internal air temperature used in the calculation was the average of air temperatures measured at various heights within the space (0.3 m, 1.5 m, 3.0 m and ridge). The slope of the line was termed the specific heat loss of the factory, defined as the heat input to maintain an average 1°C internal/external air temperature difference (i.e. W $°C^{-1}$). This analysis was carried out for all factories and an example for Unit 2 is presented in Fig. 3. From this specific heat loss value a design heat loss was extrapolated (i.e. the energy required to maintain a design internal/external temperature difference of 20°C), and also a seasonal heat loss value was deduced, in this case using the same degree days data as used for the energy targetting (Table 2) for comparison purposes. Table 5 presents the predicted design, the measured design and seasonal heat loss values for all factories.

In most cases the measured operational targets lie within the error range (2 s.d.'s) of the design targets. In addition there will be errors associated with constructional tolerances as discussed in the sections on *U*-value and air infiltration measurement. These could amount to the order of 20%. Also there are the effects of occupation (e.g. ventilation and door opening; heat loss/gain through party walls). It is therefore considered that, within the range of experimental error, constructional tolerance and occupational variations (where

Table 5. Design, revised design (based on measured U-values and air infiltration rates) and measured operational design targets, together with operational seasonal heat loss

	Energy targets			
Unit	Standard U-values infiltration (kW)	Measured U-values infiltration (kW)	Measured operational design target* (kW)	Seasonal heat loss (GJ m^{-2}/yr^{-1})
1	10.6	10.2	9.2 (1.0)	0.30
2	10.6	10.2	10.1 (1.0)	0.34
3	8.2	7.6	9.4 (0.5)	0.32
4	18.9	22.9	25.6 (2.8)	0.75
5	49.7	36.5	41.7 (6.6)	0.30
6	49.7	36.5	46.1 (6.4)	0.33
7	80.0	87.0	92.9 (9.2)	0.33
8	106.3	—	110.0 (8.5)	0.33

* Two standard deviations given in brackets.

applicable), the design energy targets were demonstrated to have been achieved in practice.

6. FACTORY HEATING

The heating systems used in the factories represented standard state of the art practice. Although the project was concerned primarily with the performance of the building fabric it is considered to be worth mentioning some aspects of the heating system performance in the monitored factories which were significantly different in terms of their heating requirements to the more traditional type of "energy inefficient" factory of say 10 or 20 years ago.

Traditionally, factory heating systems were designed generally to raise the temperature over a work zone, which may not have occupied the whole of the factory floor space. If the worker was outside this zone of heat coverage he (or she) expected to be cold. The building fabric did not contribute to the thermal environment other than to provide basic shelter from the elements. Once heat had been delivered to the prescribed area of coverage it was considered more or less to be lost. In this way the thermal environment could be termed "emitter dominant". For modern low energy buildings in general the thermal environment should not be emitter dominant, in that once the building has warmed up, the heating system should play a secondary role to the building fabric in maintaining thermal comfort. Better insulated factories, as with all low energy buildings, should now be able to contain the heat after it has been delivered to the space. However, the basic design of factory heating systems has not generally changed from the concept of providing heat coverage or emitter dominated areas.

The project factories were heated by systems traditional in concept but reduced in capacity to match the reduced design heat loss. Analysis of the internal air temperatures throughout the space and with time has indicated that there were problems of: (a) excessive vertical temperature gradients (typically 6–8°C, but up to 20°C) and (b) large temperature swings with time. These are both illustrated by the first four days of measured temperatures in Fig. 4, for unit 1 [15], heated by a warm air system (although similar profiles were experienced with unmodulated radiant systems). In this case the on/off thermostat was replaced by a modulating control, and the improvement in internal temperature profiles can be seen in the last three days of Fig. 4. Such problems

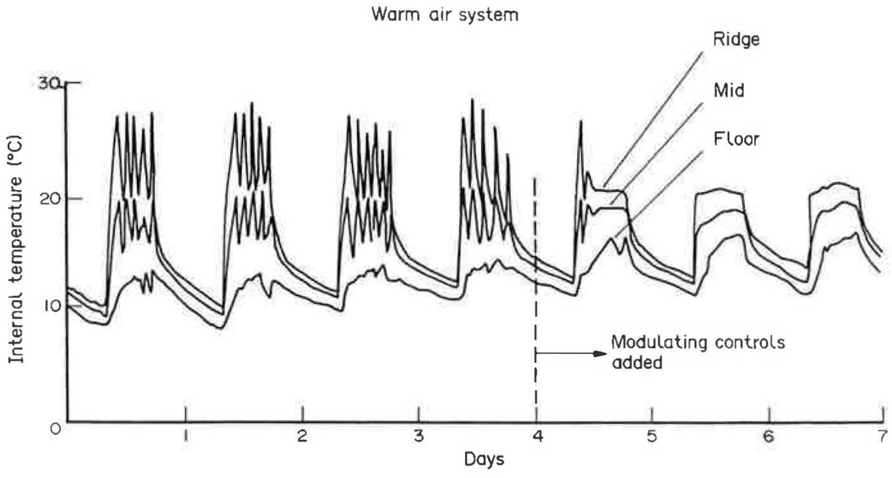

Fig. 4. The vertical variation of temperature with time over a week period for unit 1. During day 5 the on/off thermostat control was replaced by a modulating control [13].

are a potential source of thermal discomfort and energy waste. They suggest some degree of mismatch between the heating system and the building heating requirements.

The basic requirements for factory heating are to meet the fabric heat loss under a range of external conditions and to provide thermal comfort over the occupied zone. There are two problems with many current systems:

(i) When they are downrated to match the reduced design heat loss they may not be able to provide adequate heat coverage in the traditional sense. As a result, often oversized system are prescribed, which can increase the problems of control and energy inefficiency.

(ii) Low energy factories like all low energy buildings require a large turndown after initial warm up. Many current systems are not capable of modulation. Even when systems are capable of modulation there can be problems, e.g. turning down air temperature on unit air heaters can result in too low a temperature and perceived draughts; turning down surface temperature on radiant systems will result in a drop in radiant efficiency.

With many currently available factory heating systems there is clearly a difficulty not so much in the delivery but in distribution of the small amounts of heat required by low energy factories. One solution may be to separate the distribution of heat from its delivery by using the same type of mixing fans as used for temperature destratifying. For example, a floor mounted mixing fan could be used in conjunction with a unit warm air heater (or some form of a radiant system) to provide the necessary degree of heat distribution. This is a hypothetical example, but it serves to illustrate new options for heating low energy factories. Clearly this is an area where future research efforts should be directed.

7. CONCLUSIONS

Measured U-value performance was found to be higher than design predictions due: (a) to problems of installation and (b) the construction not performing as designed, i.e. either due to the materials themselves or the nature of the construction (e.g. there could be unpredicted heat loss due to ventilated cavities). There is a need to review methods of on-site construction and the WDA are doing this as a result of the findings of this work. There is also the need for further investigations into the U-value performance of cladding type constructions in practice, to determine whether or not the findings of this work (i.e. a general increase of about 10% in operational U-values) represent general standards and if so can improvements be made.

Measured air infiltration rates indicated that significant reductions (up to two thirds) are possible over the CIBSE design standards, especially in the larger (900 sq. m) units, by using good detailing and high performance components. Of special significance is the choice of a well sealed loading door. An uninsulated loading door in a small unit can account for 25% of the conductive losses and 45% of the air infiltration losses.

Design energy targets can be achieved in operation within the range of constructional tolerance. The results of this work show good agreement of operational targets with design targets.

Traditional heating systems designed to current and reduced design energy targets can as a result be mismatched to the heating requirements of the space, and could result in thermal discomfort and energy waste. There is a need to investigate methods of heating low energy factories in order to provide a distribution of heat which will match both the heat loss and thermal comfort requirements.

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