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Technical Note

Summary A study of the effects of air movement within a complex factory building is described. Air conditioning systems operated to alleviate discomfort in some parts of the factory, and to satisfy product requirements in another. The interaction of the various air conditioning systems and potential overcapacity were considered to offer scope for improvement. Environmental investigations included the use of a tracer gas to examine air transfers. It was concluded that air transfers between adjacent partitioned areas were low, enabling the adoption of a more sophisticated control strategy which would reduce the demand for conditioned air.

Air movement in a partitioned industrial environment

A C PITTS BScTech PhD
Department of Building Science, University of Sheffield, Sheffield S10 2TN, UK

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1 Introduction

This report concerns a study of the environment inside a large industrial building. In particular air movement due to both mechanically induced and natural forces has been investigated. The factory is principally involved in the manufacture of nylon fibre. This is a very energy intensive process; at the time of the study annual consumption of gas and electricity at the plant was greater than 500 TJ.

In the main manufacturing process (termed 'spinning') a nylon polymer chip feedstock is converted by melting and extrusion into yarn. Though the yarn could subsequently be modified within the plant, the spinning area accounted for the major energy use (more than 60% of the total budget). Measures introduced by the site's Energy Utilisation Engineer had improved the energy load significantly. However, one particular feature caused concern: the multiplicity of ventilation and air conditioning systems in use.

An initial investigation of the energy use around the plant (using records of monthly meter readings) indicated the importance of the air movement systems. Figure 1 shows electricity consumption for the spinning process and clearly illustrates the significance of air conditioning and ventilation with respect to the total. Note that these totals do not contain any element of refrigeration energy use (a supply of bore hole water being available for cooling). The large electrical load was commensurate with a total installed rated fan capacity of more than 1000 m^3s^{-1}. The ventilation and air conditioning systems were also important since they were responsible for the movement of vast quantities of low-grade heat about the factory in the form of warm air.

The factory buildings had been built and extended over several decades; with each extension more air conditioning systems were added. This had resulted in a multiplicity of systems which seemed poorly integrated or controlled. There appeared to be a lack of knowledge with regard to overall air movement and its effects.

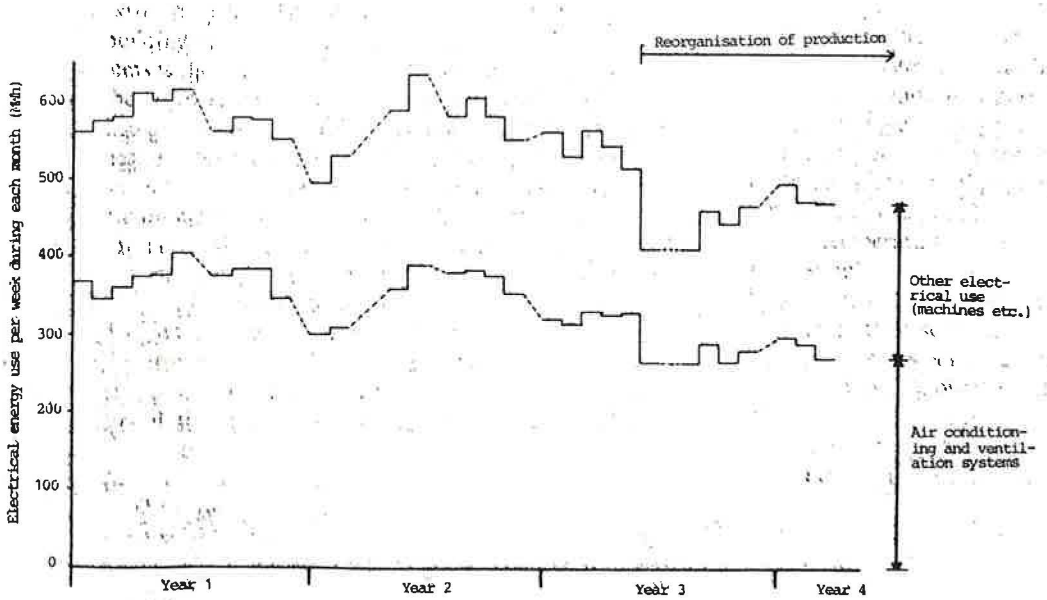

Figure 1 Electrical energy use in spinning process

2 Industrial air movement

During the last decade there has been much interest in and many studies performed on air movement. Until recently, however, such studies have concentrated on infiltration and ventilation of domestic and commercial buildings, and industrial buildings have been comparatively neglected. Baturin's[1] text on industrial ventilation is a wide-ranging and important synthesis of a number of relevant subjects. However, the industries dealt with are mainly situated within large spacious buildings in which thermal convection currents and localised air supply or extract are considered. DeGids[2,3] has worked on air movement in industrial buildings, though he and other authors who reported their work at the 4th Air Infiltration Centre Conference[4] were primarily concerned with large, single or few-cell structures. Investigations have often aimed at reducing infiltration and excess ventilation, and therefore heating costs, or gaining a better understanding of ventilation air flows (though some of the factories surveyed by DeGids were very actively process oriented). In Britain air movement has been studied as part of programmes to improve heating effectiveness as well as to improve understanding of air flow patterns and infiltration[5,6], though again dealing with fairly large open-plan factory buildings.

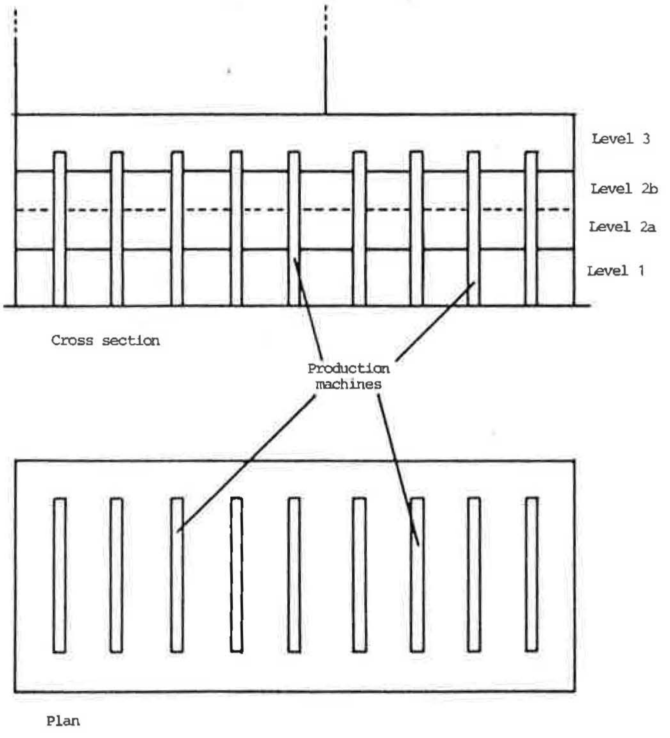

Figure 2 Spinning area layout

Thus, while there is a considerable literature on air flow in buildings, the number of industrially based projects has been limited, and these have often been restricted to single large-volume enclosures with only naturally produced air flow patterns. The main features of the plant described here were the high number of mechanical air movement systems and the machine layout of the production process which introduced both vertical and horizontal partitioning within the main building. Figure 2 is a simplified partitioning diagram.

3 The process environment

The basic functions occurring at each of the production levels shown in Figure 2 were: Level 3, delivery of nylon polymer feedstock to top of production machines; Level 2b, melting of polymer; Level 2a, extrusion of polymer into fibres; Level 1, conditioning and collection of yarn.

These processes created two types of environment requiring air conditioning. On Level 2 melting the nylon produced a very hot environment which required cooling to alleviate the discomfort of the workforce. This took the form of large volumes of fresh outside air supplied above and along each machine. During the summer the air was cooled by evaporative spray. Even with a large supply volume (and matching extract) excessive temperatures were often recorded (above 35°C and sometimes above 40°C). Level 1 had different requirements to maintain the quality of the yarn. The specified conditions were 22.5°C (±1.5°C) and 67% relative humidity (±4%). Staff were concerned that Level 1 could have operated at an overall negative pressure with respect to the outside when certain fan systems were in use. This and suspicions about the role of doors and openings in the building which faced the prevailing wind suggested that unconditioned outside air could have intruded into the critical yarn collection area.

At the start of this investigation there was little environmental monitoring; there was thus a need both to examine what was occurring in terms of air movement and to suggest possible means of improvement.

4 Initial investigation

Since the factory used a large number of fans both to supply and extract air, one of the first tests to be considered was a building pressurisation/depressurisation study using the installed ventilation systems rather than additional external fans. Such testing had already been done in North America[7,8], though the tall, office type structures investigated were very different from any industrial plant.

Unfortunately the tests were inconclusive. There were many problems with fluctuating pressure differentials and in determining flow paths. The uncontrollable opening and closing of external doors exaggerated the difficulties. It was noted, however, that the pressure measurements were sensitive to movement of the measurement location in the partitioned machinery layout.

Environmental measurements using hand-held probes were also made. Air temperature, mean radiant temperature, air velocity and relative humidity were recorded. The measurements indicated variations in readings between floor levels (which were to be expected) and variations between different areas on the same floor (which were not expected). Table 1 lists the results—each survey represents a different vertical section through the factory spinning area. Care was taken to obtain comparable results.

As well as this work, general air movement patterns were traced with a smoke generator. The smoke was produced by atomising a non-toxic paraffin oil. The patterns produced were recorded by video camera for later analysis. It was evident that there was an overall drift of air across the production areas in a roughly west to east direction. Also, in the areas adjacent to the production machines, the air flows created by the mechanical systems could be seen to produce undesired results. In some hot areas warm air was entrained into the supply flow creating a recirculation effect and reducing the cooling provided. In another area a substantial stagnation zone was found. The variations in air flow discovered may account for the differences in environmental measurements shown in Table 1.

Table 1 Environmental measurements in factory

Survey No.	Level	Air temperature (°C)	Mean radiant temperature (°C)	Relative air velocity ($m s^{-1}$)	Relative humidity (%)
1	3	17.9	23.4	0.75	48
	2b	30.8	38.7	0.75	34
	2a	24.0	36.4	0.8	41
	1	25.0	26.3	0.5	56
2	3	20.3	28.4	0.75	50
	2b	35.8	41.7	0.6	27
	2a	28.9	34.6	0.85	39
	1	23.0	27.5	0.25	59
3	3	27.2	33.1	0.6	42
	2b	38.0	40.8	0.75	34
	2a	26.1	28.2	1.25	41
	1	23.5	29.1	2.8	54

There were three main conclusions from this investigation. Firstly, that the air flows adjacent to the machines were variable, and might not always produce the most favourable environment for either worker comfort or process requirements. In some locations the systems were not operating in the way which the initial design would have intended. Secondly, in addition to the localised air movement, bulk air flow was occurring across the production area—possibly due to external influences, and finally, the high degree of internal partitioning created by the machine layout meant that even on the most general level, it was not possible to consider each production level as a single zone for air movement.

To alleviate some of the problems associated with poor air flow, at a local level, fairly simple recommendations were made to help improve the air flow distribution. The effect of the bulk air flow and the possible intrusion of unconditioned air required more detailed study.

5 Investigation of air flow

The main concern within the production environment at the factory was the maintenance of yarn quality, so further investigation was limited to the areas between the machines where the fibre was initially conditioned and collected before further processing elsewhere. Bearing in mind the conclusions already reached, it was necessary to discover whether the bulk air flow across the factory could affect the local air conditioned environment around the fibre to any significant extent.

It was decided to use nitrous oxide (N_2O) as a tracer gas to investigate air movement; in particular, that air movement which could lead to the intrusion of unconditioned air. An area towards the centre of the factory production area was chosen for the tests. This area contained several regularly spaced machines with air conditioned zones between. Nitrous oxide was liberated in the central zone and it concentration monitored in that central and the two adjacen zones using an infrared gas analyser. The acting pressur differential was measured and additional fans were posi tioned to enhance any air movement across the test are (Figure 3).

In all, twelve sampling points were used, four in eacl of the three adjacent areas. To assess the ventilation rate fo the central zone and also to examine the transfer to adjacen zones an equilibrium concentration technique was used This was attained by liberating the tracer gas at a constan and fairly high rate while waiting for concentrations t stabilise. Though there are several techniques for the inves tigation of ventilation rates using tracer gases, the equi librium concentration method would give the most reliabl results within the factory environment under consideration Liberation was confined to the central area and took plac via a mixing tube arrangement incorporating a small fan Measurements of tracer gas input rate and equilibrium con centration enabled the rate of dilution to be determined an hence the rate of influx of new air into the space.

The average equilibrium concentration was 82 parts pe million N_2O in air with a tracer liberation rate of $0.6 l s^-$ Thus the fresh diluting air influx was $7.3 m^3 s^{-1}$. This ra was determined for the central zone (B) under normal plar operation conditions and since the zones were physicall identical with similar supply and extract ducts connected t common headers, the same rate was assumed to apply f the adjacent zones (A and C).

Further tests were carried out to investigate alternati plant operating conditions. In the first all mechanical a movement systems relating to the areas between tl machines were switched off, leaving only what might l termed 'background ventilation'. This background ve tilation arose from the influence of air movement systems other areas of the factory and the action of external a movement forces. The average equilibrium concentrati achieved with a liberation rate of $0.3 l s^{-1}$ was 150 ppm. Tl indicated a diluting ventilation rate of $2 m^3 s^{-1}$. In the fir test arrangement the normal supply and extract systems the areas were again halted, but as well as background effec the additional fans shown in Figure 3 were used to create extra artificial pressure difference across the test areas about 1.3 Pa as compared with the first test. With tracer g input at $0.3 l s^{-1}$ the equilibrium concentration was 65 pp which was equivalent to a ventilation rate of $4.6 m^3 s^{-1}$.

Table 2 Tracer gas concentrations (tracer gas liberation initially into Zone B)

Test No.	Condition	N_2O liberation rate ($l s^{-1}$)	Concentration of N_2O in air (ppm) Zone A	Zone B	Zone C
1	Normal plant Operation	0.6	3	82	<1
2	Background ventilation only	0.3	30	150	8
3	Background plus additional fans	0.3	4	65	8.5

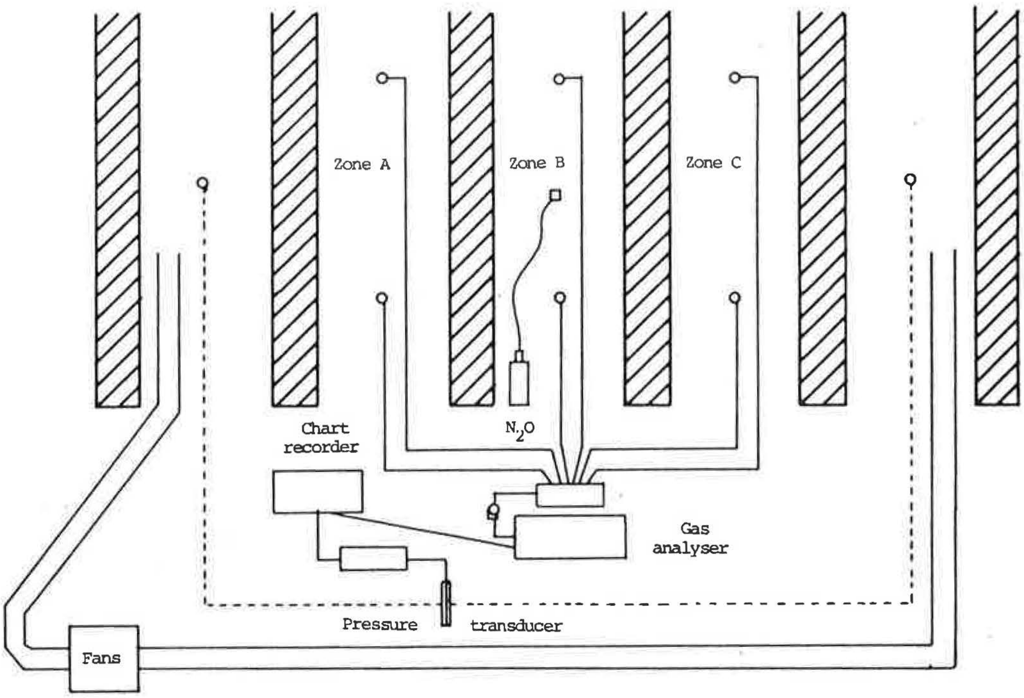

Figure 3 Layout for tracer gas investigation

Besides the equilibrium concentrations in the central monitored area (B in Figure 3), measurements were also made in the adjacent areas A and C. Average concentrations are given in Table 2.

6 Discussion

The factor of interest in the production environment was the possible intrusion of unconditioned air. The tracer gas results allowed the determination of likely air transfers. The specified ranges on normal environmental operating conditions already quoted (22.5 ± 1.5°C and 67% ± 4% RH) allowed a standard to be set which could be analysed in terms of air stream mixing. If the exchange of 10% air by volume between neighbouring zones is taken as an initial limit then the intruding, perhaps unconditioned, air may range in temperature from approximately 7.5 to 37.5°C and in humidity from approximately 30% to 95%, yet still give a mixture within the specified operating ranges. Since none of the adjacent factory areas contained air at temperatures or humidities more extreme than these wide bands it was concluded that the 10% intrusion limit was adequate.

The experiments were designed to investigate the primary air transfer between adjacent zones (preliminary trials having indicated secondary effects to be negligible). This air transfer could be assessed by reference to measured concentrations and dilution of air flow rates.

The source of tracer gas in the second zone was the air transfer from the first zone (in which the tracer was initially liberated). The rate of tracer gas input into zone 2 i_2 would equate to the gas concentration in the air leaving zone 1 C_1 multiplied by the amount of air transferred f_{12}:

$$i_2 = c_1 f_{12} \quad (1)$$

The equilibrium concentration of gas in zone 2 C_2 depended on the tracer input rate i_2 and the dilution air supply rate d_2:

$$c_2 = i_2 / d_2 \quad (2)$$

There was no attempt to identify the routes by which the tracer gas was lost from zone 2; the main objective of the investigation was the impact of air transfers from one partitioned space upon its immediate neighbours, not the secondary dispersal routes.

Table 3 Air transfers in factory

Ventilation system operation	Flow direction From	to	Flow rate ($m^3 s^{-1}$)	Intrusion rate: Based on actual air flow to zone	Intrusion rate: Based on normal air flow
Normal system operation	Zone B	Zone A	0.27	3.6%	3.6%
	Zone B	Zone C	0.09	1.2%	1.2%
Background Ventilation only	Zone B	Zone A	0.4	20%	5.5%
	Zone B	Zone C	0.11	5.5%	1.5%
Enhanced ventilation with extra fans	Zone B	Zone A	0.28	6.1%	3.8%
	Zone B	Zone C	0.6	13%	8.2%

Though there are some limitations to the technique, combining equations (1) and (2) allows the 'intrusive' air flow to be estimated:

$$f_{12} = (c_2/c_1)d_2 \qquad (3)$$

Table 3 summarises the results and indicates that if a zone experienced normal ventilation system operation then the intrusion rate was very much less than the 10% limit. With the control regime obtaining at the time of the study it was not possible to arrange for adjacent zone ventilation to be switched individually. As a result the effect of a non air-conditioned/ventilated zone next to an ordinarily air conditioned zone could not be investigated; hence the table quotes two intrusion rates—one based on the measured air supply during the particular test, the second determined using the fresh air supply under normal plant operation. So although direct calculation of intrusion rate of unconditioned air into a conditioned zone was not possible, the results obtained indicated that such intrusion was unlikely to prove significant. Even in the most extreme case investigated with additional fans used to create the potential for enhanced intrusion, the intrusion rate into a normally ventilated zone was likely to be less than 10%.

7 Conclusions and recommendations

One of the basic aims of the original study was to investigate air movement with a view to improving control and operation and reduce energy costs. The relatively low air intrusion rates between adjacent zones in the production area indicated a considerable degree of isolation of these zones. This isolation offers scope for reduced air conditioning system use, since supply and extract systems need only operate in areas of yarn production. If switching mechanisms were employed in each zone separately then a control system could be programmed to operate in line with machine production schedules. (Though general production was continuous at the factory, at any time some machines were not operated due to maintenance considerations or to allow modification or changes in yarn production.) If conditioned air wer to be supplied only to those zones actively involved ir production, there would be considerable scope for savings

Though it has been possible in this particular situatior to investigate air flows and recommend improvements, it was not possible to investigate the more general mechanisms involved. Clearly there is a need to discover more about the interactions of mechanically induced air flows and naturall produced air movement in the built environment for both open plan and partitioned areas.

Acknowledgements

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