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What is This?
Advances in cubicle design using computational fluid dynamics as a design tool

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Summary

As part of a recent animal facility refurbishment, a cubicle containment system was designed to increase the amount of experimental space and also provide containment facilities to support the holding and use of specialized animal models. In order to achieve this, a series of computational fluid dynamic (CFD) studies was undertaken to evaluate the effects of different airflows and in order to optimize ventilation, a variety of exhaust/supply arrangements and animal loads was employed. These studies showed that air delivered via two, opposed, low level ducts, at a rate of 20 air changes per hour and exhausted high in the cubicle above the rack, was the optimal configuration resulting in minimal turbulence, stagnation and entrainment.

Keywords  Computational fluid dynamics; cubicles; containment; airflow

The increasing use of transgenic, mutant and other specialized animal models has led to a downward shift in group size but has also been associated with increased technical demands relating to animal care and colony health management. At the same time there has been an increased demand for workers’ safety, especially related to protection from animal allergens, radionuclides and biohazards. As a result, animal research has shifted from work being carried out in, or adjacent to, the laboratory, into the animal facility itself, placing a greater demand for animal space to be used for experimental procedures. Hence this has created the need to maximize the use of animal facility space in order to house smaller groups of animals often with highly specialized needs, frequently requiring a higher level of containment than a standard animal room can provide. Based on the experience of workers in the United States, we considered the cubicle containment system to be the most flexible and efficient for coping with most containment needs and best suited to the separation of transgenic, mutant and inbred strains, where the maintenance of genetic integrity is paramount. In addition to our own experiences (Curry et al. 1996), the rationale for the use of cubicles, includes cost, spatial advantage, disease and genetic containment potential as described by various authors (Dolowy 1961, White et al. 1983, Ruys 1988, Hessler 1993). However, we were of the view that there were some inherent design problems in existing systems that do not result in optimum airflow relating to the benefit of the animals and staff who work within them.

To test our various hypotheses, computational fluid dynamics (CFD—Flovent, Flowmerics Ltd, Surrey, UK) was used as a software analysis tool because it would
readily support the analysis of a full range of case studies leading to the identification of the most effective airflow configuration to suit the majority of uses. The concept of CFD has long been in use and validated by the aerospace, construction and electronics industries and more recently has been shown to be an extremely effective system for modelling airflow in animal facilities [Hughes & Reynolds 1995, Hughes et al. 1996]. The use of CFD provided the means to simulate airflow across a fully comprehensive range of animal caging and environmental conditions.

Materials and methods
Design parameters were established that the team felt were important for multiple-use cubicles. Principal amongst these was the capability to contain limited chemical and/or biohazard agents and have the ability to provide positive separation of species and strains of varying microbiological quality. In order to achieve this, cubicles were designed to be capable of running in either negative or positive pressure modes. To allow for maximum flexibility the cubicles were sized to be capable of holding various species from mice to small primates using standard, commercially available animal racking without special connections for ventilation or caging.

The area available, measuring 11 m x 6 m (66 m²), was sufficient to contain a total of six cubicles supported by central procedural space [Fig 1]. The cubicles were fabricated from stainless steel panels sandwiching 40 mm thick high density polyethylene to ensure good sound and thermal isolation and insulation respectively. Cubicle access was created via three vertically rising, counter-weighted sashes, glazed with 6 mm toughened glass (Fig 2).

The cubicles were required to operate at a temperature range of 18–26 ± 2°C, with a relative humidity of 55 ± 10% and an external lighting system providing a maximum level of 400 lux at the rack face. The internal sound level was to be < 50 dBA [Home Office, Code of Practice 1989]. The whole system was to be controlled by a central computerized building management system to provide continuous adjustment for each set of test conditions.

Each bank of three cubicles was provided with its own independent and remotely sited
air supply and exhaust system with its own backup power supply, standby fans, motors and coils to ensure that all the demands of the cubicles were met. All ductwork was insulated to minimize the effect of external factors on the monitoring devices. It was also designed to provide internally smooth surfaces and sized to prevent the occurrence of any rumbling or white noise which might spread to the cubicle. In addition, all ductwork supplying/exhausting the cubicles was terminated with a flexible connection to minimize the transmission of structure borne noise.

**Case studies**

Two series of CFD case studies were undertaken. The aim of the first was to develop the immediate design parameters needed for a cubicle suite forming part of a refurbishment project and that of the second, to further refine this design in relation to a new animal facility development project.

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**Fig 3** The base case, simulating a cubicle with a ten cage rack running with no heat load at 20 ACH with a centred, high level radial type diffuser and a low level exhaust.
Series 1
The first series of 14 studies examined airflows based on existing designs, i.e. air flowing from a high level diffuser near the top of the cubicle to a low level extract point. Airflows were investigated within the cubicles, as well as in the external room housing them and the interface between these two areas. By this means it was hoped to determine that relationship between the air supply and extract points and air volumes and velocities which would minimize entrainment and turbulence in order to maximize air quality, and at the same time reduce the levels of airborne allergens. The base design simulated a cubicle running at 20 air changes per hour (ACH) with a centred, high level, four-way slot supply diffuser and single, rectangular, low level exhaust grille, with no simulated animal heat load and the rack fully centred (Fig 3). This basic case was then followed by a series of studies that compared the effects of different airflow rates and animal heat loads against different supply/extract configurations and rack positions.

Animal heat loads were simulated at either 200 or 400 W/rack, based on rat heat emissions of 1 W/100 g of body weight [Hughes et al. 1996]. The heat load was modelled to simulate either 100 or 200, 200 g rats, caged and evenly distributed across a single rack.

Results: Series 1
This first series showed that neither changing the location of the supply air diffuser to an off centre position nor providing multi-level exhausts had an effect on airflow velocity or direction in the cubicle, nor was there any improvement regarding airflow by exhausting at multi-levels. In fact the base design proved to be the best arrangement. It was also shown that either increasing airflow beyond 20 ACH (up to 40 ACH) or halving the animal load produced little improvement in performance.

The simulation did show, however, that the location of the rack within the cubicle is vital if unstable airflows are to be avoided. With the rack fully centred under the supply diffuser, Fig 4 shows the CFD predicted variations in velocity and temperature over time, producing an oscillation effect. It was found that the most stable pattern of airflow was predicted when the rack was sited towards the back of the cubicle where it was not directly under the supply diffuser (Fig 5). With all the cubicle doors closed the simulation predicted good separation of air between the cubicle and the external room. There was no leakage of air from the top of the cubicle to the room, or vice versa, and hence no effect on their relative airflow patterns. On opening fully the bottom sash of a single cubicle there was an escape of warm air from the top of the cubicle into the room environment, coinciding with cooler room air flowing back into the cubicle at low level (Fig 6). There was no effect on the adjacent cubicles as long as their doors remained closed. The CFD did predict however, that should two adjacent cubicle sashes be opened simultaneously, some air could flow between them, especially if equipment or personnel were moving in the room disturbing its airflow patterns. As long as the fresh air was supplied at the top of the cubicle, CFD predicted that it would immediately go down to floor level and the air that had been warmed by the animals' body heat would rise to the top of the cubicle (Clough 1987). Therefore, in effect, cool fresh air always flowed in low and warm air exited high over the top of the racks.

Series 2
Despite our general satisfaction with the function of the initial designs we felt that it might be possible to improve air quality still further by minimizing entrainment and re-circulation within and outside the cubicle environment. The limiting factor that prevented maximal air quality appeared to be resistance and obstruction to incoming fresh air caused by the warm air from the animals in their cages, which could not be overcome by increasing supply velocity even above 40 ACH. The second series of studies was therefore designed to take advantage of the buoyant forces generated by the heat of the animals themselves (Clough 1987, Hughes et al. 1996) and to investigate supplying air at low level and removing it at a...
Fig 4: With airflow simulated at 20 ACH and a 400 W heat load, with the rack fully centred, the computational fluid dynamics predicted an oscillation effect over time.
high level. Utilizing the results from Series 1, all further investigations were carried out using an airflow rate providing 20 ACH, with a single high level exhaust set on the back wall to capture rising air loaded to 200 or 400 W. In addition, several air supply and exhaust configurations in the external room were studied in order to determine the best way to ventilate the room with respect to minimizing air flowing from the cubicle into the room and vice versa when a single cubicle door was opened. Comparisons were made between the use of 3 or 4 radial type supply diffusers combined with two, low level, wall exhausts with a soffit supply/exhaust system described by Hughes et al. (1996).

Results: Series 2
The CFD simulation showed that with no heat load, air would rise from the low level supply diffuser through the empty rack and out of the extract diffuser in one pass. With a heat load of 200 W, the velocity of the air
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Fig 6. On fully opening the sash doors, the computational fluid dynamics predicted the escape of warm air from the top of the cubicle into the external room. Replaced by cooler air flowing into the cubicle at low level.
Fig 7 A cubicle with two low sidewall diffusers and a high level exhaust with a heat loading of 400 W. Aided by the buoyant forces of hotter rising air, air velocity increases and passes directly out of the exhaust duct with little entrainment.
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increased quickly as it crossed the face of the rack and was exhausted at the top of the cubicles with minimal entrainment. Increasing the load to 400 W did cause some increased turbulence at high level but the air still moved directly to the exhaust with little or no entrainment (Fig 7). The velocity vectors and temperature contours showed the same picture here as with the 200 W loading, with entrainment occurring only at high level in isolated 'eddies'. Case studies comparing the different air supply and exhaust systems within the room housing the cubicles showed that the soffit system placed towards the rear back wall was the best arrangement where the CFD simulation showed immediate high level capture of air with minimal entrainment which was significantly better than the airflow system in the original cubicle design where air was supplied at high level.

While the cubicle doors were closed and because sash design tolerances were minimized to prevent leakage, air was contained within each cubicle by means of the directional flow. With the cubicle in negative pressure mode, air is still contained when the doors are not fully closed but it was initially assumed that air would, inevitably, escape when the doors were fully open. However, even in this instance, it was possible to capture and direct escaping air and so maximize air quality by minimizing exposure of entrained air at operator face level. This was achieved by installing a stand-alone air containment and capture system in the room holding the cubicles (Fig 8). This stand-alone, 'soffit system', uses the same 'warm, rising air' principle and captures the hot air rising at high level from the cubicle, immediately extracting this air, with minimal entrainment.

**Discussion**

Previous work on airflow rate and distribution within cubicle systems appears to have been largely based on a 'rule of thumb' approach or the use of empirical data, with selected design preferences being tested using full or scale modelling techniques. Although costly, full scale models may be justified against the cost of the eventual installed system, the actual number of samples tested will be limited due to time constraints and the inability to easily adjust the model to provide a comprehensive test bed. In the present study we evaluated current designs in order to develop a cubicle system that would provide the most effective and efficient airflow configurations across a range of species, racking designs and stocking densities.

Experiences of evaluating airflow in animal rooms have demonstrated that much of the past thinking may not have been optimal (Hughes & Reynolds 1995). The combination of air supplied via two low level diffusers placed along the side walls, with a single high level exhaust on the back wall of the cubicle proved to create the most satisfactory airflow arrangement for the cubicle. This design consistently outperformed conventional type cubicles, where air is supplied at high level and exhausted at low levels, regardless of airflow rate, diffuser type or cage rack load. The soffit system proved to be the best arrangement for the external cubicle room by capturing escaping air at a high level with little or no re-entrainment on opening a cubicle sash.

All the studies performed showed that cubicle systems can operate effectively and efficiently as containment systems. Room contamination on opening the sash can clearly be managed to good effect but the fact that some air still entrains and escapes, albeit at a low concentration, means that these systems have containment limitations and still require procedural control if cross contamination between adjacent cubicles is to be avoided. However, the efficiency of the cubicle/soffit arrangement in capturing escaping air does help to minimize the risk of cross contamination by improving the purge rate of contaminants and maximizing the dilution factor. This arrangement should also improve operator safety in relation to the exposure of animal allergens due to the significant reduction of recirculation and entrainment of air in the outside rooms.

The concept of locating air handling equipment remote from the cubicle, coupled
Fig 8  A soffit air supply/extraction system installed in the external room captures hot rising air escaping from the cubicle when the sash doors are opened.
with the design features to minimize noise generation and transmission, proved to be a key element in controlling noise levels and ensures exacting environmental control. Humidity was best controlled by zoning the banks of cubicles but due to the importance of temperature control, each cubicle had its own separate re-heat coils to ensure that this was within the required specifications.

References


