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Building Serv. Eng. Res. Technol. 14(4) 143–149 (1993) Printed in Great Britain

Summary Experiments were carried out on open-flued gas and oil boilers in a test house at the Building Research Establishment, Garston, to find out what parameters affect combustion gas spillage. The experimentation consisted of testing the pressure difference and extract fan flow rate at which spillage occurred. The results showed that in a large number of cases spillage will result if an open-flued gas appliance and air extract fan are running concurrently. Spillage was not encountered with the oil boiler which had a pressure jet burner. Any fan installed in the same room as an open flued gas appliance or an oil fired appliance with a vaporising plate burner should have a maximum capacity of 20 l s^{-1}, and fan and appliance should pass a suitable spillage test.

Extract fan flow rates resulting in spillage

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Received 12 September 1992, in final form 10 June 1993

1 Introduction

Combustion appliances require air to support combustion of fuel and with which to dilute the waste gases. An open-flued combustion appliance draws this air from the space in which it is sited. If this space is depressurised, the air available to the appliance is limited and it may have difficulty in drawing in adequate fresh air. When the level of depressurisation exceeds a critical value, the exhaust gases spill into the space in which the appliance is sited. Higher levels of depressurisation cause total reversal of flow in the flue. Spillage is potentially hazardous since the space surrounding the appliance, which is generally living space, begins to fill with harmful products of combustion.

An initial investigation and literature search on the subject suggested that domestic air extract fans could, under certain circumstances, create a level of depressurisation high enough to cause spillage, and full flow reversal in the flue. Fatalities resulting from carbon monoxide poisoning from gas appliances average about 40 per annum with more non-fatal accidents(1). Some of these are due to spillage because of blocked flues, poorly designed flues or poor ventilation practice (which may include an extract fan in the same room as an open-flued combustion appliance).

An experiment to determine the circumstances under which spillage occurs was therefore designed and set up.

1.1 Cold vent establishment pressure test

One test in particular was used to test the likelihood of the burnt gases spilling into the room instead of flowing safely up the flue. This test originated in Canada where the Centre for Building Science at the University of Toronto tested about 40 houses for boiler venting problems. The cold vent establishment pressure(2) (CVEP) test is a measure of the maximum pressure difference across the flue at which an open-flued boiler can start up from cold correctly. The CVEP is found by depressurising the room with the boiler in, (by running the fan at a high speed) to a low pressure relative to outside so that air is sucked into the room down the flue. The boiler is then started up and the burnt combustion gases flow out of the dilution inlet and into the room. The fan flow rate is gradually turned down so that the internal/external pressure difference decreases. At a certain point this pressure difference will be such that the boiler is able to overcome the effect of the fan and the combustion gases begin to flow up the flue in the correct and safe manner. This point is the cold vent establishment pressure.

The maximum level of depressurisation that can be safely maintained in a room is less than the CVEP. The CVEP shoud not be attainable by all the depressurising devices in the room or dwelling working together, otherwise the risk of spillage presents itself.

If the flue is warm due to cycling of the boiler and the boiler cuts in, a higher pressure difference is needed to prevent it from working properly, because the heat in the flue walls warms the air in the flue, making it more buoyant. The CVEP is critical because it is the lowest pressure difference at which spillage can occur and which the boiler will be unable to overcome. For this reason the CVEP and the fan flow rate required to create this critical pressure difference were chosen as the main criteria for experimental research.

1.2 Hot vent reversal pressure tests

The hot vent reversal pressure (HVRP) is the minimum internal/external pressure difference at which a boiler, which has been operating correctly for some time so that the flue is hot, spills combustion products into the room.

To test for the HVRP an open-flued boiler is left running until the temperatures in the flue have stabilised. The extract fan is then turned on and its flow rate gradually increased until hot gas is detected spilling from the dilution air inlet. The internal/external pressure difference when this first occurs is the hot vent reversal pressure.

1.3 Oil-fired boiler tests

The oil-fired boiler used had a pressure jet burner, which is believed to be the only type of burner currently used in new domestic oil boilers in the UK (NB: some oil-fired cooking appliances may have other types of burner). The boiler has a fan which takes in the correct quantity of air to allow for complete combustion and adequate dilution. Oil is pressurised and burnt in a firing chamber. The only air inlet to the boiler and flue is through the fan, so for gases to reverse down the flue, the boiler's combustion air fan has to stall or fail. The test was therefore to see if the boiler fan could withstand an adverse pressure applied by a room extract fan.

2 Experimental set-up

The tests done by Timusk *et al.*(2) in Canada were carried out in inhabited houses with all internal doors left open. The depressurisation in this case would not be as great as if the extract fan had been in the same room as the combustion appliance and the door to that room had been shut. It is common in the UK for a boiler to be sited in the same room (usually the kitchen) as an extract fan. For this reason it was decided to coduct tests in the kitchen of a test house on site at the Building Research Establishment, Garston. The tests were carried out with the kitchen door shut.

The testing was done in such a way as to minimise the number of unknown variables. With all the tests being done in the same room of one house, discrepancies due to a different distribution of air leakage, different dimensions giving rise to different pressure distributions between inside and outside etc., could be ignored.

In order to gain a fair understanding of how different variables affect the operation of open-flued boilers, three different flues and three different boilers were tested. Three air bricks were built into the wall on one side of the kitchen. These were sited at three different heights and at different distances from the boilers and extract fan. A fan with a flow rate variable up to $300\ \mathrm{l\ s^{-1}}$ was chosen. CVEP tests were done with the kitchen at two different degrees of air-tightness.

For the HVRP tests the air-tightness of the room ($11\ \mathrm{ac\ h^{-1}}$ at 50 Pa) and the air brick size ($70\ \mathrm{cm^2}$) and position were kept constant throughout. Thus the tests were conducted in an environment which should have produced an almost linear relationship between fan flow rate and the square root of internal/external pressure difference. Four flue/boiler combinations were tested at a variety of different internal/external temperature differences and wind conditions.

3 Study design

3.1 Flues

The flues used were:

(*a*) 0.125 m nominal internal diameter, stainless steel, twin-wall, insulated;

(*b*) 0.2 m nominal internal diameter, stainless steel, twin-wall, insulated;

(*c*) 0.2 m nominal internal diameter, masonry flue, refractory concrete liner.

With this combination of flues, it was possible to test the influence on the behaviour of the system of:

(i) a different internal flue diameter by comparing the two twin-wall stainless steel systems; all other variables (e.g. surface roughness, thermal conductivity of flue wall) being constant;

(ii) different materials used in the flue construction by comparing the two 0.2 m flues; all other variables (e.g. dimensions) being constant.

The flues were built to British Standard specifications next to each other on the east wall of the kitchen. All had the same height, positioning of bends and cowl type.

3.2 Boilers

The boilers used were:

(*a*) natural gas, open-flued, wall hung, 8.8 kW output

(*b*) natural gas, open-flued, wall hung, 17.6 kW output

(*c*) oil-fired, pressure jet burner, floor standing, 19 kW output.

The two gas boilers were of the same design but different outputs so as to avoid the influence on the results of different boiler dimensions, and the effect of the size of heat output could be observed.

3.3 Air bricks

Three air bricks were installed. They were positioned at different heights (0.27 m, 0.82 m and 2 m from the floor) and different distances from the boilers. It was possible to vary the air brick opening from $0\ \mathrm{cm^2}$ to $200\ \mathrm{cm^2}$. During tests with the gas boilers the air brick size was set at:

(*a*) closed

(*b*) the area recommended by Approved Document J to the Building Regulations(3) and the relevant British Standards

(*c*) as (*b*) plus $50\ \mathrm{cm^2}$ (as recommended in *BS5440*(4) where an air extract fan is fitted in the same room as an open-flued combustion appliance).

These values were as given in Table 1.

Table 1

Boiler type	Output (kW)	Air brick size ($\mathrm{cm^2}$)		
		(*a*)	(*b*)	(*c*)
Gas	8.8	0	20	70
Gas	17.6	0	70	120
Oil	19	0	77	127

It was thus possible to test for the suitability of the recommended air brick sizes, the effect if any, of siting the air brick near to or far from the boiler, and by changing the air brick height, whether the stack effect in the room would be strong enough to have any influence.

A heat sink capable of dissipating 17 kW (at 40°C temperature difference) was erected outside the kitchen so that any one of the boilers could be run continuously, and so that a constant temperature could, if required, be maintained in the boiler heat exchanger.

4 Measurement

Data were recorded at 2 s intervals for up to 6 min periods using a data logger. Measurements were taken of average wind speed, wind direction, fan flow rate, gas flow to boiler, pressure differences between the kitchen and several locations (see Figure 1), temperatures at several locations (see Figure 1). From the recordings it was possible to follow closely what was happening in the boiler/flue system: which way the gases were flowing and at what temperature.

4.1 Air-tightness

The fan pressurisation technique was used to measure the air-leakage rate of the kitchen (volume $34\ \mathrm{m^3}$). The initial air-leakage rate of the room was 22 air changes per hour

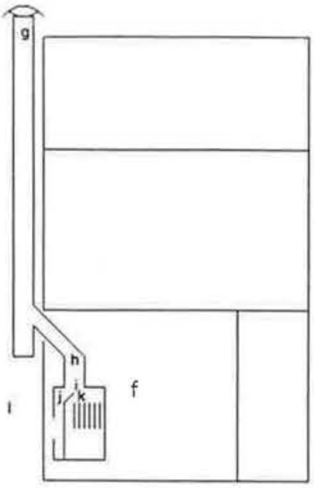

Figure 1 Location of measuring devices (not to scale): Temperature measured at f, g, h, i, j, k, l; Pressure difference measred between f and g, f and h, f and j, f and k, f and l; CO_2 and CO concentration measured at f; Wind speed and direction measured

(ac h^{-1}) at a pressure difference of 50 Pa. After extensive testing many of the adventitious air leakage paths were sealed up so that the room had an air-leakage rate of 11 ac h^{-1} at 50 Pa.

4.2 Environmental conditions

External temperature and the wind speed and direction were measured. The internal temperature was varied to achieve internal/external temperature differences of between 0 and 20 K. Average wind speed was recorded. A pressure tapping on the roof gave some indication of when gusts in the wind occurred. As far as was possible a set of tests was conducted under two or three different wind conditions.

A gas analyser was used to monitor the levels of carbon dioxide and carbon monoxide in the kitchen.

The sine of wind direction was measured and multiplied by wind speed, giving a vector for the pressure exerted on the air bricks on the east wall. Thus a west wind, which resulted in a negative pressure on the outside of the east wall and consequently a tendency for the air to be drawn out of the kitchen, was allotted a value of –1 times wind speed. An east wind was evaluated as +1 times wind speed. North and south winds were assumed not to exert pressure on the east wall and were allotted readings of 0. Thus theoretically the higher the wind vector value, the higher the pressurisation value of the kitchen. This is a very simplistic approach; in reality the wind speed and direction are constantly changing and eddies in the air flow near an air brick complicate matters still further.

5 Statistical analysis

The complete set of data collected was processed using a computer multi-regression package. The package was used to determine the most significant factors affecting spillage.

6 Gas boiler results

6.1 CVEP tests

A total of 305 successful CVEP tests were carried out on the two gas boilers in Spring 1991. Figure 2 shows the results of the first tests involving the small boiler and the 12.7 cm (5") stainless steel flue. The regression line of CVEP on wind speed shown in Figure 2 has a high correlation coefficient of 0.92. The fan flow rate for these results varied between 35 and 126 l s^{-1}, with a strong correlation of 0.87 between wind speed and critical fan flow rate (CFFR) (Critical fan flow is the flow rate of the fan at the CVEP, i.e. the minimum fan flow rate likely to cause spillage). There was a tendency for the tests with larger areas of air brick to give higher critical fan flow rates. The correlation between wind speed and CFFR increases to between 0.89 and 0.92 if the tests are grouped by air brick size. The size of air brick appears to have no effect on the CVEP; see Figure 2.

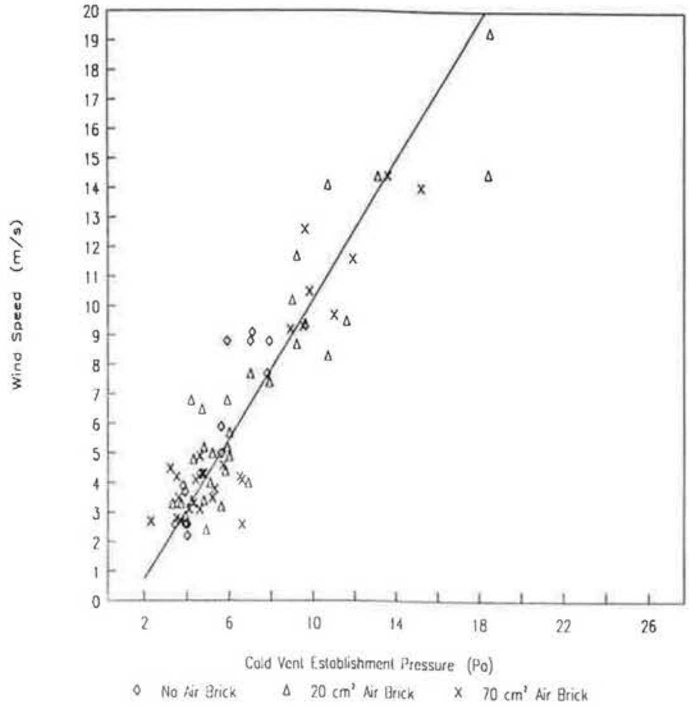

Figure 2 CVEP versus wind speed for small gas boiler and 12.7 cm (5") stainless steel flue by air brick size with regression line of CVEP on wind speed

The other combinations of boiler/flue system are not shown in such detail, but the results followed a similar trend to that for the small boiler/small flue. The correlation with wind speed was not so strong, but as before, in the tests done with the smaller air brick, the boiler continued to spill combustion products until the fan flow rate had been reduced further than it had with larger air brick sizes. Again the size of air brick seemed not to have an effect on the CVEP.

All the tests done with the two gas boilers and the two stainless steel flues at a room air-leakage rate of 22 ac h^{-1} at 50 Pa are shown in Figure 3. The results have been divided into groups showing the air brick size used during the test. The general trend of these results is that the larger the air brick size, the higher the critical fan flow rate. This is independent of boiler size, flue size and internal/external temperature difference. For clarity the points have been divided into four groups (one for each air brick size) and regression lines of critical fan flow rate against wind speed drawn—see Figure 4. The correlation coefficients for these regression lines are 0.53, 0.82, 0.79, 0.64 for air brick sizes of 0, 20, 70, 120 cm^2 respectively.

All the tests done with the two gas boilers and all three flues at a room air-leakage rate of 22 ac h^{-1} at 50 Pa are shown in Figure 5. This time the results are presented by flue type. Figure 6 shows the regression lines of CVEP on wind speed of the stainless steel flues (correlation coefficient 0.66) and of the masonry flue (correlation coefficient 0.78) for the same data. The masonry flue tests tend to give a higher CVEP for equivalent wind speeds than the tests on the stainless steel flues.

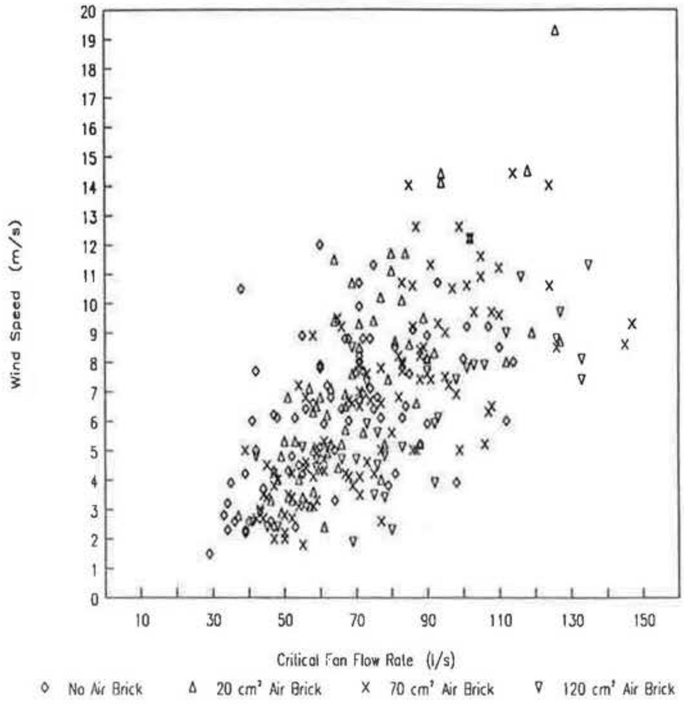

Figure 3 CFFR versus wind speed for both gas boilers and both stainless steel flues with different sizes of air brick

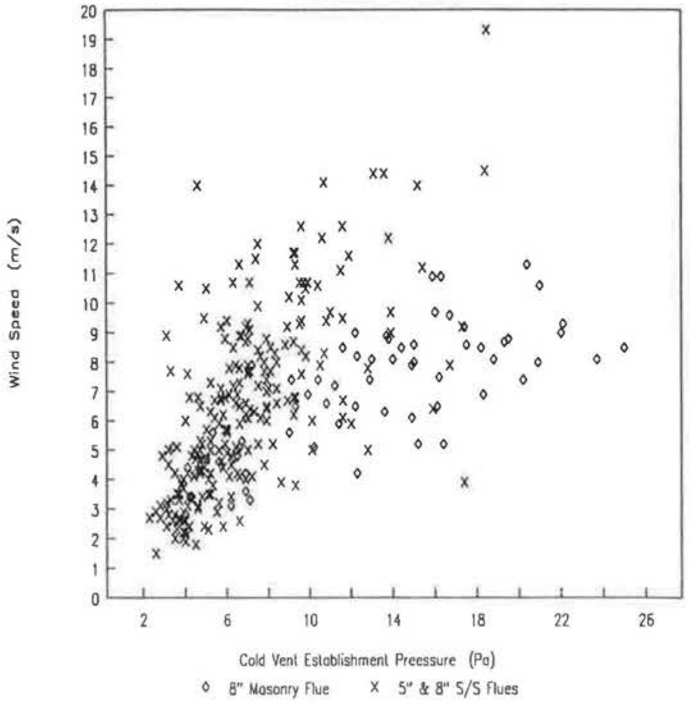

Figure 5 CVEP versus wind speed for all tests, divided by flue type

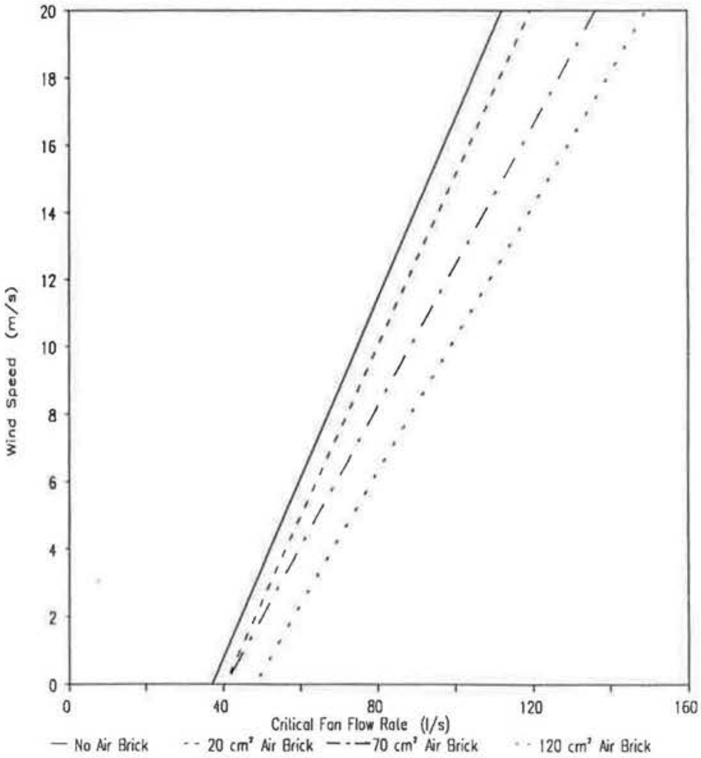

Figure 4 Regression lines of CFFR on wind speed by air brick size for both gas boilers and both stainless steel flues

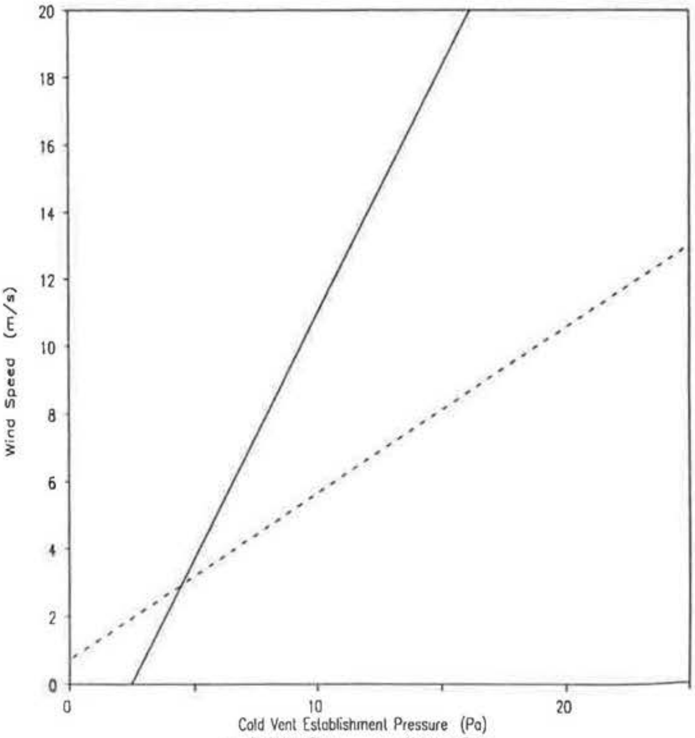

Figure 6 Regression lines of CVEP on wind speed by flue type for all tests

The air leakage rate of the kitchen was halved to 11 ac h^{-1} at 50 Pa and further tests were carried out using the small gas boiler, 12.7 cm (5") stainless steel flue and all four air brick sizes. Statistically the measured CVEPs from these tests come from the same population as the results from the previous tests with the stainless steel flues. The critical fan flow rates are all below 60 l s^{-1} even with a 120 cm^2 air brick and wind speeds of up to 12 m s^{-1}; several of them are below 30 l s^{-1} — see Figure 7.

The results from the multi-regression computer package showed that the dependent variables for the critical fan flow rate in order of significance were wind speed, air tightness of kitchen, flue type, air brick size, internal/external temperature difference.

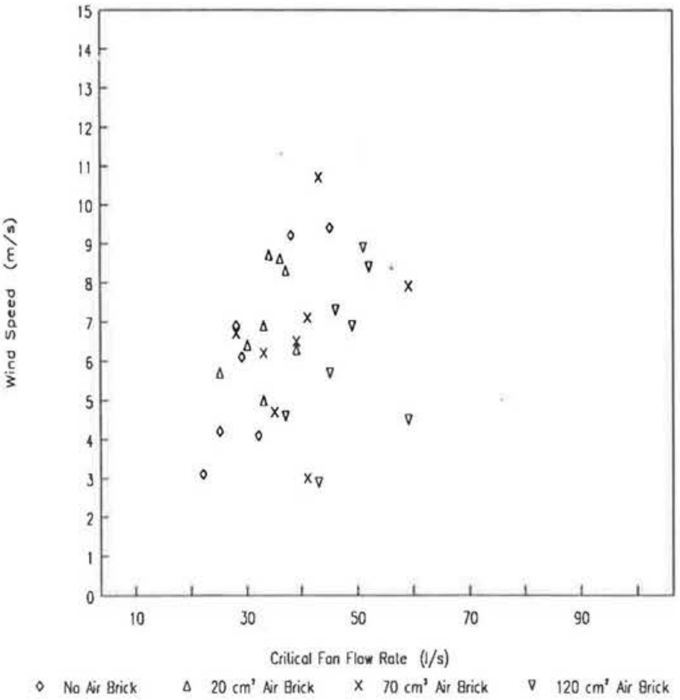

Figure 7 CFFR against wind speed for 8.8 kW boiler, 12.7 cm (5" stainless steel flue and 11 ac h^{-1} at $\Delta p = 50$ Pa.

The dependent variables for the cold vent establishment pressure in order of significance were wind speed, flue type, internal/external temperature difference.

The size of boiler, the wind direction pressure vector, the flue diameter, and the height and position of air brick appeared to have no significant effect on the CVEP or CFFR.

6.2 *HVRP tests*

A total of 64 HVRP tests were carried out in Summer 1991 in the same room as the previously described CVEP tests. The points of the beginning of flow reversal (when hot gas first starts to spill from the dilution inlet) and full reversal (when the flue reverses fully with cold air coming down the flue from outside) were recorded — see Table 2.

Table 2

Flue /boiler combination	Mean internal/external Δp (Pa)	
	At first spill	At full reversal
12.7 cm (5") S/S flue, small gas boiler	13.8	18.5
20 cm (8") S/S flue, small gas boiler	11.3	15.5
12.7 cm (5") S/S flue, large gas boiler	18.1	28.8
20 cm (8") masonry flue, large gas boiler	12.1	17.5

The range of pressure differences for the commencement of spillage was from 8.5 to 20 Pa. The range for complete reversal was 12 to 34 Pa.

When the HVRP data were analysed using the multi-regression package, the wind and temperature difference were not found to be significant in the pressure difference required to reverse a hot flue.

6.3 *Indoor pollution levels*

During all tests, the level of CO_2 and CO were monitored in the kitchen. The maximum levels recorded were 8.7×10^3 ppm $CO_2 = 0.87\%$ and 15.2 ppm CO.

7 Oil-fired boiler results

The oil-fired boiler was tested and under no conditions did any combustion gas spill from it into the kitchen. The room was depressurised to 200 Pa and the fan supplying combustion air to the boiler still managed to draw in air. The proportion of oxygen in the flue gases was seen to decrease with an increase in pressure difference. An increase in Δp of 1 Pa reduced the proportion of oxygen in the flue gases by 0.025%. The proportion of oxygen in the flue gases recommended by the manufacturers is 4.5%. Incomplete combustion does not begin to occur until the proportion of oxygen is about 1%. Thus the effect of any pressure difference which could be created by a domestic extract fan was of no significance to the boiler.

8 Discussion

Examining the order of significance of dependent variables for CVEP and CFFR, it can be seen that the air-tightness of the kitchen and the air brick size are significant determinants of the critical fan flow rate, but not of the cold vent establishment pressure. That is because they are contributing factors to the pressure difference created by the fan — thus in an airtight kitchen a boiler will fail at the same pressure difference as in a more leaky one.

In theory, the height of the air brick above floor level should have an influence on the CVEP. Temperature in a room changes with height above the floor. The room air density and the pressure relative to the outside also change. The resulting change in pressure difference between two air brick heights should thus change the measured CVEP. No such difference was recorded in these tests, so it appears that other factors overshadowed this effect.

The higher CVEP values obtained for the masonry flue than for the stainless steel flues could be a result of the rate of heat conduction from the internal flue surfaces. At the start of a CVEP test when the fan draws cold air down the flue, the stainless steel flue will cool down quickly because of its high thermal conductivity. The high mass and thermal inertia of the masonry flue mean that it stays warm for longer. This warmth could add buoyancy to the air inside the flue, helping to establish venting at a higher fan flow rate.

The results for the HVRP tests are, as expected, somewhat higher than those for the CVEP tests; however, there are still some conditions in which a small domestic fan could create enough negative pressure to cause spillage from a hot flue.

From Table 2, the flue/boiler combination which gave the lowest pressure difference at which spillage occurred with a hot flue was the small boiler/20 cm (8") stainless steel flue. This is because this boiler heats the flue to only a moderate temperature (50 – 70 °C); there is thus not so much buoyancy in the flue to counteract the negative pressure exerted by the fan. The large boiler/12.7 cm (5") stainless steel flue combination performed best; higher pressure differences are required to reverse the flow in the flue. In this case the higher flue temperature (110 – 130 °C) gave a good upward draught.

When the large boiler was used, the masonry flue performed significantly worse than the small stainless flue. This is probably because the internal surface of the masonry flue was at a lower temperature.

Wind speed and internal/external temperature difference did not appear to affect the HVRP. At high wind speeds, however, the flue temperature may cease to be the dominating factor and the wind might have more influence on the HVRP. A domestic extract fan is unlikely to cause flue reversal at the pressures at which this is likely to occur.

The Health and Safety Executive[4] long-term exposure limits for CO_2 and CO are 5×10^3 ppm and 50 ppm respectively; the short-term exposure limits are 15×10^3 ppm and 300 ppm respectively. Although the levels recorded in the kitchen do not appear to be dangerous in the short term, they may be harmful over longer periods. It must also be remembered that the boilers tested were new and properly commissioned. Older boilers could well be less efficient in combustion and produce a larger proportion of harmful gases.

The results from the programme of experiments show that the cold vent establishment pressure for a particular boiler/flue system is constant when there is no wind and no internal/external temperature difference. The CVEP should not be exceeded while the boiler is likely to be started up from cold, and the HVRP should not be exceeded at any time while the boiler is running. The critical fan flow rate for the flue/boiler system depends on the air leakage characteristics of the room. A method of predicting the level of depressurisation that would be caused by a given air extract rate in a room/building would then determine whether or not the system is safe.

The Building Research Establishment has a database of air leakage rates for over 280 houses in the United Kingdom. These air leakage rates have been calculated from fan pressurisation tests, that is a series of tests correlating fan flow rate with level of house depressurisation. This information extends only as far as the house as a whole, and no data are available for individual rooms.

Without carrying out a fan pressurisation test, whether a given situation would be safe can only be guessed. It is therefore wise not to install an extract fan and open-flued appliance in the same room or building unless the safety of the proposed installations is determined from a fan pressurisation test or suitable spillage test. *BS5440*[5] includes a spillage test for evaluating the safety of boilers when they are installed. As has been shown in this paper, the wind can create extra upward draught in the flue. If a spillage test is done on a windy day, the extra upward draught could mean that a boiler/flue system will pass the spillage test, whereas on a calm day it would fail the same test. A more sophisticated spillage test which takes into account wind speed and/or level of room depressurisation would be more satisfactory. In any case a fan size producing more than 20 $l\ s^{-1}$ is not recommended in a room which contains an open-flued appliance. In no tests was spillage detected at less than 20 $l\ s^{-1}$ fan flow rate — see Figure 3.

The size of air brick required for an appliance is based on the needs for combustion air supply. Since larger boilers require more air for complete combustion and dilution flow, the air brick size that they require is calculated to be larger than for a smaller boiler. As United Kingdom dwellings are, on the whole, leaky buildings, the calculated minimum air brick size required to supply the combustion air is generally only a fraction of the total leakage area. When a room in which an open-flued combustion appliance is sited approaches a high level of airtightness, there is a high probability that spillage will occur. The wind or indeed the stack effect are quite capable of causing a depressurisation of 2 Pa, which in a few cases was enough to make the boilers tested spill at start-up.

As has been shown by the CVEP experiments, boiler size is not a significant factor which will determine the CFFR. It may therefore be more appropriate for air bricks to be sized according to the airtightness of the room in which the boiler is sited, rather than the boiler size. It is, however, not a simple proposition to measure the airtightness of every room in which an open-flued boiler is to be installed.

The experiments reported upon so far have been concerned only with boilers. There are other combustion appliances which require a flue to vent their burnt gases safely outside. Gas fires and decorative fuel-effect fires fall into this category. They are often installed in old fireplaces when a solid fuel fire is removed. The same spillage principles apply to these appliances, i.e. the CVEP should not be exceeded while an appliance is likely to be started up.

Cases have been reported of combustion gases spilling when gas fires and extract fans were installed in different rooms in the same flat[†].

Although there appeared not to be a problem with the oil-fired boiler, caution must be observed when installing oil appliances of the pressure jet burner type. Under depressurisation it is possible for combustion products to leak out into the room if the boiler casing and flue are not properly sealed.

Some oil-fired cookers manufactured for the United Kingdom market and older appliances have vaporising plate burners. These have open flues and may be susceptible to spillage.

9 Conclusions

The most serious situation is the case of a combustion appliance with a cold flue cutting in when a fan has been running for some time (CVEP). The main factor influencing the cold vent establishment pressure is the wind speed. At lower wind speeds (i.e. of less than 6 $m\ s^{-1}$) spillage of combustion gases occurred at or below a fan flow rate of 60 $l\ s^{-1}$ with all boiler/flue combinations and with all air brick sizes tested. This is below the flow rate of a typically sized domestic fan.

If a spillage test is carried out on a windy day the boiler may operate correctly with the fan running at full speed. However, the boiler may not in fact be safe on a day when the wind speed is lower.

It was possible under some conditions to reverse the flow in a hot flue of a correctly venting boiler using a typically sized domestic fan.

The fan flow rate that will cause spillage varies widely. As a guide, however, if a fan is installed in the same room as an open-flued combustion appliance it should have a capacity of no more than 20 $l\ s^{-1}$. Even then it should be classed as safe only if it has passed a suitable spillage test conducted with a cold flue and low wind speed.

The oil-fired boiler did not spill, even when the internal/external pressure difference was as high as 200 Pa. Combustion was affected slightly by the depressurisation but not at such a level as to cause any concern.

All domestic oil boilers currently on the United Kingdom market are of the pressure jet burner type, so it should be safe to install extract fans in the same room as this type of appliance.

[†] Private communication: N C Murrell, South Somerset District Council

There are some older oil-fired appliances with vaporising plate burners, and some oil-fired cookers are still made with vaporising plates and open flues, so the spillage test and 20 l s^{-1} rule should also be applied to these.

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