NATURAL DRAUGHT OPEN FLUE DIAMETERS

Flue gas velocity

A flue must eject products of combustion from its terminal at sufficient velocity to ensure effective dispersal. The *Clean Air Act Memorandum on Flue Heights* specifies a minimum exit velocity of **6 m / s** for natural draught systems from 333 kW up to 2 MW net heat input. However, excessive velocity at the base of a flue can create **turbulence** at the appliance injector which may affect burner operation.

Flue gas velocity depends on the **cross-sectional area** of the flue. Smaller cross-sections force gases to move faster. Flues must be sized to ensure that flue gas velocity stays within acceptable limits specified by the appliance manufacturer.

Flue flow rate

The CO_2 % reading obtained from a combustion analyser or from manufacturer's instructions is a measure of carbon dioxide in a **dried** sample of flue gases, i.e.:

$$\mathrm{CO_2\ \%} = \frac{\mathrm{Vol.\ CO_2}}{\mathrm{Vol.\ total} - \mathrm{Vol.\ H_2O}} \times 100$$

$$\therefore \quad \mathrm{Vol.\,total} = \frac{100 \times \mathrm{Vol.\ CO_2}}{\mathrm{CO_2\ \%}} + \mathrm{Vol.\ H_2O} \qquad (1.0)$$

Avogadro's Law applied to stoichiometric combustion gives the respective volumes of products of combustion. For a natural gas appliance of gas rate **G** (m^3 / h):

$$\mathrm{Vol.\ CO_2} = \mathrm{G} \qquad (2.0)$$

$$\mathrm{Vol.\ H_2O} = 2\,\mathrm{G} \qquad (2.1)$$

Substituting (2.0) and (2.1) into (1.0) gives an equation for the total flow rate of flue gases (m^3 / h) in terms of gas rate:

$$= \frac{100\,\mathrm{G}}{\mathrm{CO_2\ \%}} + 2\,\mathrm{G} \quad = \left(\frac{100}{\mathrm{CO_2\ \%}} + 2\right)\mathrm{G} \qquad (2.2)$$

If the fuel supply is at temperature T_0 (°C) and the gross flue temperature is T (°C) the thermal expansion factor of the flue gases is:

$$\left(\frac{T + 273}{T_0 + 273}\right)$$

Combining this factor with equation (2.2) gives the total thermally-expanded flue flow rate (m^3 / h) that the flue must carry:

$$= \left(\frac{T + 273}{T_0 + 273}\right)\left(\frac{100}{CO_2\ \%} + 2\right) G \qquad (2.3)$$

Dividing by 3600 gives **F**, the **Flue flow rate** in **m^3 / s**

$$\mathbf{F} = \left(\frac{\mathbf{T + 273}}{\mathbf{T_0 + 273}}\right)\left(\frac{\mathbf{100}}{\mathbf{CO_2\ \%}} + \mathbf{2}\right)\left(\frac{\mathbf{G}}{\mathbf{3600}}\right) \qquad (3.0)$$

To find the circular flue **Diameter D** (m) which will give the required **Velocity V** (m / s) at the specified flue flow rate F (m^3 / s) we note that:

$$F = \text{Cross sectional area} \times V$$

$$\therefore \qquad \text{Cross sectional area} = \frac{F}{V}$$

i.e.

$$\pi \left(\frac{D}{2}\right)^2 = \frac{F}{V}$$

$$\mathbf{D} = \sqrt{\frac{\mathbf{4\ F}}{\mathbf{\pi\ V}}} \qquad (4.0)$$

Rearranging (4.0) gives flue gas **Velocity V** (m / s) in terms of **Diameter D** (m):

$$\mathbf{V} = \frac{\mathbf{4\ F}}{\mathbf{\pi\ D^2}} \qquad (5.0)$$

Worked examples

1. According to manufacturer's instructions a boiler has a gross heat input of 124.5 kW, a gross secondary flue temperature of 100 °C and a secondary flue CO_2 percentage of 4.5 %. What flue diameter is needed to achieve a flue gas velocity no greater than 3.5 m / s at the base of the flue?

A conversion chart gives the appliance gas rate G as 124.5 ÷ 10.6 = 11.75 m^3 / h. Assuming fuel gas / ambient temperature is 15 °C, the flue flow rate will be:

(3.0) $$F = \left(\frac{T + 273}{T_0 + 273}\right)\left(\frac{100}{CO_2\ \%} + 2\right)\left(\frac{G}{3600}\right)$$

$$= \left(\frac{100 + 273}{15 + 273}\right)\left(\frac{100}{4.5} + 2\right)\left(\frac{11.75}{3600}\right)$$

$$= (1.2951) \times (24.22) \times (0.003264)$$

$$= 0.1024\ \mathrm{m^3/s}$$

The flue diameter required to achieve this flue flow rate at a velocity of 3.5 m / s is:

(4.0) $$D = \sqrt{\frac{4\ F}{\pi\ V}}$$

$$= \sqrt{\frac{4 \times 0.1024}{3.142 \times 3.5}} = 0.193\ \mathrm{m} = \mathbf{193\ mm}$$

2. A boiler with net rated heat input 240 kW has a 150 mm diameter flue. The measured gross secondary flue temperature is 112 °C and the CO_2 percentage in the secondary flue is 3.8 %. Is the flue gas velocity within the acceptable range? (The manufacturer states it should be between 2 and 7 m / s).

Using a conversion chart, gas rate $G = 240 \div 9.5 = 25.26$ m^3 / h. Assuming that fuel gas and ambient temperature are 15 °C the flue flow rate will be:

(3.0)
$$F = \left(\frac{T + 273}{T_0 + 273}\right)\left(\frac{100}{CO_2\ \%} + 2\right)\left(\frac{G}{3600}\right)$$

$$= \left(\frac{112 + 273}{15 + 273}\right)\left(\frac{100}{3.8} + 2\right)\left(\frac{25.26}{3600}\right)$$

$$= (1.3368) \times (28.32) \times (0.007017)$$

$$= 0.2657\ \mathrm{m^3/s}$$

The flue gas velocity V is:

(5.0)
$$V = \frac{4\,F}{\pi\,D^2}$$

$$= \frac{4 \times 0.2657}{3.142 \times (0.150)^2} = 15\ \mathrm{m/s}$$

This flue gas velocity is too high. The flue will have to be replaced by a larger one. If we specify the target velocity as 4.5 m / s, we obtain a diameter of:

(4.0)
$$D = \sqrt{\frac{4\,F}{\pi\,V}}$$

$$= \sqrt{\frac{4 \times 0.2657}{3.142 \times 4.5}} = 0.274\ \mathrm{m} = \mathbf{274\ mm}$$

Assumptions and simplifications

The volume of water vapour in atmospheric air has been assumed to be negligible. In reality, atmospheric air may contain between 0.2 % and 4 % water vapour. This means in the worst case (high humidity) the equations will underestimate flue flow by 4 %.

CO_2 % values are assumed to be taken from perfectly dried flue gas samples.

CO_2 % values are assumed to be taken from a perfectly mixed (homogeneous) volume of flue gases. In reality, some stratification will be present due to laminar flow. The effects of stratification on CO_2 measurements can be reduced by averaging readings from different positions within the flue.

Flue gases have been assumed to follow Avogadro's Law and the ideal gas equation of state. This assumption is reasonable since real gases closely approximate ideal gases at high temperatures and low pressures.

The equations have been developed for circular flues but may easily be adapted for rectangular flues.

The equations may be adapted for other hydrocarbon fuels by suitable amendment of equations (2.0) and (2.1).

Note that a downdraught diverter takes in additional air, so different CO_2 and temperature values will be needed for any calculations relating to a secondary flue.