Effects of hydrogen addition to the fuel jet on the velocity field in a two separated jets configuration in non-reacting flow

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Abstract The development of oxy-fuel burner with highly separated jets of fuel and oxidizer presents attractive perspectives because reactives separation generates a better thermal efficiency and a reduction of pollutant emissions by dilution effect. However, the flow instability limits the geometric dilution effect. A new fuel, called hythane, is a promising mixing between natural gas, with a hydrogen volume fraction lower than 20%. Hythane has the advantage of considerably modifying the properties of the fuel, thereby preserving the distribution installation. Owing to the high diffusivity and reactivity of hydrogen in combustion, the use of hythane solves instability problems of the flow linked to the separation of the reactives. The oxy-fuel burner is made up of two non-ventilated nozzles, the first supplies hythane flow and the second nozzle supplies pure oxygen. The distance between the nozzles varies from 60 to 100 mm. This experimental study is led in a non-reacting configuration in order to focus on the effects of hydrogen addition in the fuel on the velocity profile, the turbulence intensity and the turbulent kinetic energy. In non-reacting flow, the Particle Image Velocimetry, setup in two perpendicular planes (XZ-plane and YZ-plane), allows to obtain 2-D images of the flow and to deduce the instantaneous two-dimensional velocity fields. From the PIV measurement in the XZ-plane and in the YZ-plane, the evolution of the root mean square (RMS) of the three components of velocity can be studied permitting to deduce the influence of the hythane on the turbulent kinetic energy.

The results show that the high molecular diffusivity and low density of hydrogen sensibly modify the radial profile of mean velocity near to the nozzle. The study of the RMS velocity of the three components of velocity ($U_x', U_y'$ and $U_z'$) shows a significant difference of the fluctuation of the three components of velocity proving the characteristic non-symmetrical of burners with two separated jets. The study of the turbulent kinetic energy $k$ as a function of hydrogen addition shows that the jets interact more in upstream with the surrounding fluid and the maximum peak of turbulent intensity appears for a height less important. Moreover, the more the jets are moved away, the more the turbulent kinetic energy is important.

In this kind of this oxy-fuel burner, the hythane is a viable solution to ameliorate the mixing between the different jets without changing the process geometry and with a low cost.

1. Introduction

The evolution of pollution standards associated to strict regulations motivates the fall of fuel consumption and has resulted in an optimized performance of combustion chambers. A new generation of burners with separated fuel and oxidizer injectors shows attractive perspectives for industrialists. This kind of burner has proved great potential for the reduction of nitrogen oxide emissions (Sautet et al. 2006), since the combination of dilution effect and the nozzle separation of these burners favor the drive of combustion products in the non-reacting zone between the jets (Boushaki et al. 2009). The distance between the nozzles influences the flow dynamics acting on the location of the mixing (the region where the jets start to interact and mix together). The further the nozzles are moved away, the more the jets interact upstream in the flow, favoring the dilution of burned gases (Yon et al. 2012). However, the high dilution of reactants by burned gases in combustion chamber is limited by flame instability.

A mixture of natural gas and hydrogen, called hythane, has the advantage of considerably modifying the properties of the fuel, thereby preserving the distribution installation Due to the
properties of hydrogen found in the combustion process, specially the high molecular diffusivity, wide flammability limits, high flame speed, and low ignition energy (Choudhuri et al. 2000, Cozzi et al. 2006), hydrogen in the fuel allows combustion systems to operate with lean fuel mixtures. An increase of flammability limits in the presence of hydrogen offsets the harmful effects of lean combustion, such as local extinction, energy losses by radiation as well as flame stretching (Briones et al. 2008, Tseng 2001).

To limit NOx emissions in burners with separated jets, the air is substituted with pure oxygen, which is referred to an oxy-combustion. In air combustion, nitrogen results in a low combustion yield and high energy consumption because the nitrogen contained in the air acts as energy ballast. The complete substitution of air with oxygen leads to an improved heat yield, a rise in the adiabatic flame temperature (2200 K for CH4-air, 3090 K in CH4-oxy-combustion) (Perthuis 1983) a fuel consumption reduced by 50%, and, from an environmental point of view, a decrease in the nitrogen oxide formation (of up to 95%) because of the reduced nitrogen quantities in the oxidant (Genies 1996). However, a rising flame temperature favors nitrogen oxide formation via the NO thermal mechanism. In an oxy-fuel burner, NOx production is a result of the effects of air infiltration due to small cross-section opening allowing the exhaust of flue gases, the presence of N2 in the fuel, flame radiation, and aerodynamic straining (Sung et al. 1998). The findings on oxy-flames from burners with separated nozzles can be transposed to burner systems functioning with air because the recirculation rates are similar. In industrial processes, air used as an oxidant is often enriched in oxygen (from 30% to 40%), and tendencies found in a pure oxygen setup are therefore completely transposable.

Previous studies have proved that the high molecular diffusivity and the low density of hydrogen improve the mixing between the jets but decrease the size of the recirculation zone (Yon et al. 2012). With hythane, the jets interact more upstream in the flow and the mixing quality is better. The present study is conducted in non-reacting flow from a separated jet burner to gain an understanding of the influence of the hydrogen addition on the flow aerodynamics. The evolution of the root mean square (RMS) of the three components of velocity has been investigated permitting to deduce the influence of the hythane on the turbulence intensity and on the turbulent kinetic energy. The study of the velocity components in the XZ-plane and in the YZ-plane in non-reacting flow allows to highlight the non-symmetrical characteristic of burners with two separated jets and the importance of the recirculation zone of burned gases.

The results of this experimental study are essential for numerical studies because the data are obtained for all the components of velocity (Ux, Uy and Uz), and the turbulent kinetic energy obtained from the measurement of RMS velocity in the XZ-plane and YZ-plane, is investigated. This experimental study is a data base to compare numerical studies on burner with two separated jets.

The experimental setup consists of a burner of 25 kW functioning with hythane and pure oxygen, situated in the bottom wall of the combustion chamber. A study of the jet aerodynamics through Particle Image Velocimetry (PIV) allows to characterize flow aerodynamics. In the first part of our work, we studied the evolution of the turbulence intensity along the Z-axis as a function of the hydrogen volume fraction in the fuel. In the second part of our study, the measurements of the velocity fields in the XZ-plane and in the YZ-perpendicular plane allow to study the turbulent kinetic energy along the hythane jets as a function of the hydrogen volume fraction in the fuel (from 0% to 20%) and the distance between the nozzles. All these data have never been investigated before and are essential to understand the impact of hydrogen addition on the mixing between the two jets and particularly, the effects on the recirculation zone.
2. Experimental setup and measurement techniques

The aim of this study was to investigate the effects of the hydrogen addition in the fuel considering the distance between the nozzles (from $D=60$ mm to $D=100$ mm) and the hydrogen volume fraction in the fuel (from $\alpha_{H2}=0\%$ to $\alpha_{H2}=20\%$) with the global equivalence ratio equals to the stoichiometry ($\Phi=1$). The burner depicted in Figure 1 consists of two non-ventilated jets: a hythane jet (natural gas and hydrogen) and a pure oxygen jet. The separation distance between the nozzles ($D$) varies from 12 to 100 mm. The internal diameter of the nozzles was $d=6$ mm.

![Diagram of the burner with 2 separated jets](image)

The natural gas has a density of 0.83 kg.m$^{-3}$ and a volume composition of 85%CH$_4$, 9%C$_2$H$_6$, 3%C$_3$H$_8$, 2%N$_2$, 1%CO$_2$, and traces of higher hydrocarbon species. The hydrogen volume fraction in the fuel, $\alpha_{H2} = \rho_{H2} \dot{m}_{H2} / (\rho_{H2} \dot{m}_{H2} + \rho_{NG} \dot{m}_{NG})$ varies between 0% and 20% (with $\dot{m}$ and $\rho$ denoting the mass flow rate and the density, and subscripts $H2$ and $NG$ representing hydrogen and natural gas, respectively). The oxygen has a purity of 99.5% and a density of 1.354 kg.m$^{-3}$ (at 1 atm and at 15 °C). The fuel flow rate ($\dot{m}_{FUEL}$) and the exit velocity of hythane ($U_{FUEL}^0$) depend on the hydrogen volume fraction in the fuel blend ($\dot{m}_{FUEL} = \dot{m}_{NG} + \dot{m}_{H2}$). For the pure natural gas configuration ($\alpha_{H2}=0\%$) in stoichiometric proportion, thermal power $P=25$ kW, $\dot{m}_{FUEL} = 0.55$ g.s$^{-1}$ and $U_{FUEL}^0 = 23.7$ m.s$^{-1}$.

The flow rate and the exit velocity of oxygen are fixed whatever the configuration and correspond to the value calculated for a thermal power of 25 kW in stoichiometric proportions ($\Phi=1$), thus $\dot{m}_{O2} = 1.954$ g.s$^{-1}$ and $U_{O2}^0 = 51.3$ m.s$^{-1}$.

For security reasons in non-reacting configuration, the oxygen and the natural gas were substituted with air because without combustion, the unconsumed gases could accumulate and the least energy source could lead to serious fallout. The work of Sautet et al. (2006) shows that the difference of density which appears during the substitution of natural gas and oxygen with air has only influence far from the burner, that is to say outside our study fields (0 to 50d) and experimentally, Boushaki et al. (2009) has shown that there is not notable difference between the aerodynamics of the flow composed of natural gas/oxygen and the use of air. To keep the volume flow rate and the exit velocity in the substitution of natural gas by air and oxygen by air, the mass flow rate of air has been recalculated.
The regulation of the air flow substituting the natural gas, the air flow substituting the oxygen and the hydrogen flow rates were controlled by sonic throats connected to pressure gauges with an accuracy of ±0.7%.

Table 1 summarizes the parameters of this experimental study including natural gas, hydrogen and oxygen flow rates (\(\dot{m}_{\text{NG}}, \dot{m}_{\text{H}_2}\) and \(\dot{m}_{\text{O}_2}\)), the fuel exit velocity, and Reynolds number, in reacting and non-reacting flow.

<table>
<thead>
<tr>
<th>Parameters of the study</th>
<th>Thermal Power (P_s=25, \text{kW})</th>
<th>Inside diameters of the jets (d=6, \text{mm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction</td>
<td>(\dot{m}_{\text{NG}})</td>
<td>(\dot{m}_{\text{H}_2})</td>
</tr>
<tr>
<td>0% (\text{H}_2)</td>
<td>0.8099</td>
<td>23.7</td>
</tr>
<tr>
<td>5% (\text{H}_2)</td>
<td>0.7985</td>
<td>24.4</td>
</tr>
<tr>
<td>10% (\text{H}_2)</td>
<td>0.7874</td>
<td>25.5</td>
</tr>
<tr>
<td>15% (\text{H}_2)</td>
<td>0.7765</td>
<td>26.5</td>
</tr>
<tr>
<td>20% (\text{H}_2)</td>
<td>0.7660</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Particle Image Velocimetry (PIV) was used to study the non-reacting flow aerodynamics. This non-intrusive method allowed to obtain 2-D images of the flow and to deduce the instantaneous two-dimensional velocity fields.

A double-pulsed Nd-Yag laser (Big Sky CFR200, Quantel) with a wavelength of 532 nm and a frequency of 10 Hz was used as a light source (120 mJ/pulse, pulse duration of 8 ns). An optical system consisting of 3 consecutive lenses created the laser sheet with a thickness of 500 µm and a height of 80 mm. A CCD camera with a dynamic range of 16 bits (2040*2040 pixel\(^2\), Image Pro X Lavision) was oriented perpendicularly to the laser sheet. A lens with a focal length of +85 mm (1:14.1 Nikkor, Nikon) was placed perpendicularly to the light source and collected the signal of Mie scattering emitted by the oil seeded particles in the non-reacting flow (tracers with a diameter from 3 to 4 µm). An interference filter (532 nm, 3 ±0.6 nm bandwidth, 35% peak transmittance minimum) was used to reject the bright luminosity from the oxy-flame in front of the lens of the PIV setup. To determine the dynamic fields of the flow, calculations of the cross-correlation images were carried out by the Davis software to find the average particle displacement in each sub region of the image. The interrogation window dimensions were 64*64 pixels\(^2\) with a coverage of 50%, and hence a grid step of 32 pixels. Post processing was carried out to detect and correct the aberrant vectors that appeared in the cross-correlation calculations. The sub pixel displacement was estimated by means of Gaussian peak fitting. A maximum displacement of eight pixels would correspond to less than 2% uncertainty in the final velocity measurement. To characterize the flow and to improve spatial resolution, it was necessary to take measurements of four different heights: 0 - 93.5 mm, 58 - 172 mm, 136 - 250 mm, and 212 - 328 mm, with a spatial resolution of the interrogation windows of 2.93*2.93 mm\(^2\), 3.57*3.57 mm\(^2\), 3.57*3.57 mm\(^2\), and 3.64*3.64 mm\(^2\), respectively. This allowed us to study the different pertinent zones of the flow in order to describe the convergence zone, the fusion zone (where the two jets begin to mix and interact), and the combination zone (where the flow tends to have similar behavior to a single jet).

The processing of 500 image pairs made it possible to obtain 500 instantaneous velocity vector fields for each height and configuration. The mean velocity field was obtained by averaging the 500 instantaneous fields.
Figure 2 shows the mean two-dimensional velocity field and the characteristic zones of the flow with the two separated jets for the configuration, $\alpha_{H_2} = 20\%$ and D=60 mm.

This study focused on the effect of the hydrogen addition and the separation of the nozzles on dynamic fields in the convergence zone. In order to investigate all the velocity components in the upstream of the flow, it was necessary to use Particle Image Velocimetry in the 2 perpendicular planes (XZ-plane and YZ-plane). Figure 3 displays the images of the seeded particles in the XZ-plane and in the YZ-plane in non-reacting flow for a distance between the nozzles equals to 60 mm and a hydrogen volume fraction equals to 0%. This figure shows, in the two perpendicular planes, instantaneous, mean and RMS velocity fields. This allows to study the velocity radial components ($U_x$ and $U_y$) and the longitudinal component ($U_z$) of the velocity, and RMS radial components ($U'_x$ and $U'_y$) and the RMS longitudinal component ($U'_z$).

Table 2 groups the different magnifications and time intervals $\Delta t$ between two images versus the distance between the nozzles in the XZ-plane and the YZ-plane.

![Figure 2. Mean two-dimensional velocity fields (Non-reacting flow, $\alpha_{H_2}= 20\%$ and D=60 mm).](image)

<table>
<thead>
<tr>
<th>Magnification (mm.pixel$^{-1}$)</th>
<th>D= 60 mm (XZ-plane)</th>
<th>D= 80 mm (XZ-plane)</th>
<th>D= 100 mm (XZ-plane)</th>
<th>YZ-plane, ethane jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification (mm.pixel$^{-1}$)</td>
<td>0.0461</td>
<td>0.0684</td>
<td>0.0804</td>
<td>0.0525</td>
</tr>
<tr>
<td>$\Delta t$ (µs)</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
Fig. 3. (a) Images of the seeded particles in the XZ-plane and (a') in the YZ-plane – (b,b') Instantaneous and (c,c') mean velocity fields – (d) RMS velocity fields of the component $U_x$ – (d') RMS velocity fields of the component $U_y$ – (e) RMS velocity fields of the component $U_z$ in the XZ-plane and (e') in the YZ-plane (Non-reacting flow, D= 60 mm, $\alpha_{H2}$=0%)
3. Results and discuss

3.1 Velocity fields and fluctuations in non-reacting flows

For the study of the mean and RMS velocity fields, only results concerning the D=60 mm configuration are presented in this paragraph. Figure 4 shows radial profiles of the longitudinal velocity at different heights from exit plane. The classical distribution of the longitudinal velocity in a multiple-jet configuration is found, with a maximum in the center of the jets and a minimum between the jets. In the initial zone, each jet follows its own evolution, and then the jets start to interact.

![Fig. 4. Radial profiles of the longitudinal velocities at different heights from the burner, in the non-reacting (D=60 mm, \(\alpha_{H_2}=0\%\))](image)

The hydrogen addition leads to an increase of 18% of the fuel exit velocity, from \(U_{\text{FUEL}}^{0} = 23.7 \text{ m.s}^{-1}\) for \(\alpha_{H_2}=0\%\) to \(U_{\text{FUEL}}^{0} = 27.6 \text{ m.s}^{-1}\) for \(\alpha_{H_2}=20\%\). Figure 5 displays the radial profiles of mean velocities focused on the hythane jet, (a) for \(Z=110\) mm, (b) \(Z= 50\) mm and (c) \(Z=10\) mm as a function of the hydrogen volume fraction. Near to the nozzle exits (\(Z=10\) mm), it is observed that the maximum velocity for the configuration with a hydrogen volume fraction of 0% and 20% is respectively equal to \(28 \text{ m.s}^{-1}\) and \(33 \text{ m.s}^{-1}\). With hydrogen addition to the fuel, radial profiles of mean velocities show an increase of 18% of the maximum velocity, which is the same increase as the fuel exit velocity calculated in the description of the experimental setup. For the height of 50 mm, the addition of 20% of hydrogen in the fuel rises the maximum velocity of 9% (from \(U_z = 24.1 \text{ m.s}^{-1}\) to \(U_z = 26.3 \text{ m.s}^{-1}\)), and for \(Z= 110\) mm, the maximum velocity rises of 7% (from \(U_z = 13.7 \text{ m.s}^{-1}\) to \(U_z = 14.7 \text{ m.s}^{-1}\)). The influence of the hydrogen addition on the longitudinal component \(U_z\) is less and less significant while the height in the flow increases. Far from the burner,
the high molecular diffusivity of hydrogen reduces the longitudinal velocity. In non-reacting flow, hydrogen addition has a significant effect on the maximum velocity near to the nozzle exit, and downstream in flow, the high molecular diffusivity of hydrogen favours the longitudinal component ($U_z$) to have the same evolution than a pure natural gas configuration. From an aerodynamics point of view, hythane modifies the longitudinal velocity of flow near to the burner but keep the flow velocity behaviour in the combination zone.

From the P.I.V measurement in the XZ-plane and in the YZ-plane, the evolution of the root mean square (RMS) of the three components of velocity can be studied. Longitudinal RMS velocity along the centerline of the hythane jet ($X=-30$ mm, $Y=0$ mm) of the $U_x'$, $U_y'$ and $U_z'$ components are displayed on Figure 6 as a function of the hydrogen volume fraction. For three components of RMS velocity, a peak of RMS velocity appears for a height of 40 mm. Due to the high mean longitudinal velocity along the centerline, the results of Figure 7 indicate that the turbulence is more important for $U_z'$ component. After the maximum value of $U_x'$, the decrease of the turbulence of the $U_x'$ component is less significant than $U_y'$ and $U_z'$ components. In non-reacting flow, the oxygen jet placed on the X-axis interferes with the hythane jet and reduces the decrease of the turbulence of the $U_x$ component. The significant difference of the fluctuation of the three components of velocity proves the characteristic non-symmetrical of burners with two separated jets.

For the three components of velocity, the hydrogen addition increases the turbulence along the centreline. Near to the nozzle exits, up to $Z=20$ mm, hydrogen in the fuel not modify fluctuation of the flow, but downstream in the flow the turbulence is more important. With 20% of hydrogen addition, the maximum values of $U_x'$, $U_y'$ and $U_z'$ increase respectively of 3%, 16% and 22%. This shows that high molecular diffusivity of hythane increases the turbulence zone favouring mixing with the ambient air and between the jets themselves.

**Fig. 5.** Radial profiles of mean velocities focused on the hythane jet, for $Z=110$ mm (a), $Z=50$ mm (b) and $Z=10$ mm (c) as a function of the hydrogen volume fraction ($D=60$ mm)
Fig. 6. Longitudinal RMS velocity along the centreline of the hythane jet (X=30 mm, Y 0 mm) of $U_x'$, $U_y'$ and $U_z'$ components (D=60 mm)

3.2 Turbulence intensity

From the mean and RMS longitudinal velocity along the centerline of the hythane jet (X=-40 mm), the turbulence intensity is studied in the convergence zone. The turbulence intensity equals to $U_z'/U_z$ along the fuel jet. Figure 7 shows turbulence intensity along the centreline of hythane jet according to the hydrogen volume fraction. Whatever the hydrogen addition, the turbulence intensity increases along the jet. This rise is due to a high decrease of the longitudinal velocity (Figure 5), a high increase of the longitudinal turbulence before the peak of fluctuation and a small decrease of the RMS component after the maximum peak of turbulence (Figure 6). This increase of the turbulence intensity favours the mixing of the fuel with the surrounding fluid and with the oxygen jet. Figure 7 displays that hydrogen addition increase the turbulence intensity. The high molecular diffusivity increases up to 50% the turbulence intensity. Hythane is very efficient to increase the turbulence intensity and in consequence the mixing of the fuel jet with the oxidant.

Fig. 7. Turbulence intensity along the centreline of hythane jet according to the hydrogen volume fraction (D=80 mm).
Figure 8 shows the effect of the distance between the nozzles on the turbulence intensity along the centerline of hythane jet. This figure displays that near the burner (up to \( Z = 20 \) mm), the turbulence intensity is similar whatever the configuration. But far to the burner, the increase of the distance between the nozzles improves the turbulence intensity. This result is linked to the rise of the size of the recirculation zone located between the nozzles (Dugué et al. 2006). The more distance between the nozzles is important, the more the size of the recirculation zone is high. The recirculation zone favours the mixing between the jet and increases the turbulence in the flow.

3.3. Turbulent kinetic energy

From the measurement of the RMS of the three components of velocity \((U_x', U_y' \text{ and } U_z')\), the turbulent kinetic energy \(k=0.5(U_x'^2+U_y'^2+U_z'^2)\) can be deduced. Figure 9 displays the turbulent kinetic energy \(k\) along the centerline of hythane jet according to the hydrogen volume fraction. In burner with separated jets, the energy decay occurs as soon as the hythane jet interacts with the surrounding fluid and precisely the interaction of the centerline of the hythane jet with the recirculation zone (Mazellier et al. 2010). With hydrogen addition, the jets interact more upstream with the surrounding fluid and the maximum peak appears for a less important height. Figure 9 shows that with hydrogen addition, the turbulent kinetic energy is more important. This is due to the increase of the turbulence of the three components of velocity along the centerline hythane jet.

The study of the turbulent kinetic energy according to the distance between the nozzles (Figure 10) shows that the more the jet are moved away, the more the turbulent kinetic energy is important. However, the energy decay occurs for the same height whatever the configuration. This result means that the recirculation zone interacts with the centerline of the hythane jet at the same height \((Z=42 \text{ mm})\).


4. Conclusion

An experimental study in non-reacting flow in a burner with two separated jets according to the hydrogen addition and the distance between the nozzle has been investigated. From PIV, the aim was to obtain 2-D images of the flow and to deduce the instantaneous two-dimensional velocity fields. The measurements of the velocity fields in XZ-plane and in the YZ-perpendicular plane allow to study the three components of velocity $U_x$, $U_y$ and $U_z$, and their respective fluctuations ($U_x'$, $U_y'$ and $U_z'$). The results of radial profiles of the mean longitudinal velocities show that hydrogen addition effect on the longitudinal component $U_z$ is less and less significant while the height in the flow increases. From an aerodynamics point of views, hythane modifies the mean longitudinal velocity of flow near to the burner but keep the mean flow velocity behaviour in the combination zone.

The study of the turbulence intensity along the hythane jet shows that hydrogen addition increases the velocities fluctuation intensity. Hythane is very efficient to increase the turbulence intensity and in consequence the mixing of the fuel jet with the oxidant and the surrounding fluid.

The turbulent kinetic energy along the hythane jet as a function of the hydrogen volume fraction is investigated from the fluctuation of the three components of velocity is XY-plane and YZ-plane. The turbulent kinetic energy is an important data to investigate the impact of hydrogen addition on the mixing between the two jets and particularly the effects of the recirculation zone. With hydrogen addition, the jets interact more in upstream with the surrounding fluid and the maximum peak of turbulent intensity appears for a height less important. The study of the turbulent kinetic energy according to the distance between the nozzles shows that the more the jet are move away, the more the turbulent kinetic energy is important.

This experimental study of the effects hythane on the velocity field in a two separated jets configuration show that hythane is a viable solution to ameliorate the mixing between the different jets without changing the process geometry and with a low cost.
References:

Dugué J, Riffart S (2006) Recent developments in oxy-combustion and potential applications in refinery furnaces 7th European Conference on Industrial Furnaces and Boilers, INFUB7 18–21