Numerical investigation of the effect of constant velocity and constant residence time scaling criteria on the natural gas MILD combustion

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Abstract
This paper concerns with effect of scaling on performance of MILD combustor when increasing its geometry and thermal throughput from the 0.58 MW prototype to its scaled-up versions of 5.8 MW. The constant velocity (CV) and constant residence time (CRT) scaling approaches were used in this work. Their performances were simulated with a numerical model for MILD combustion which was thoroughly validated against existing experimental data. It was found that despite MILD condition could be successfully maintained with both scaling approaches up to the scaling factor of 10, the effect of CV scaling could lead to elevated NOx emission due to increase in flow retention time in hot environment. The results were also discussed in term of Damköhler number. Despite of promising technology of MILD combustion for low-NOx emission, care must be taken on NOx emission level when scaling up with large scale factor under the CV criteria. As for the CRT criteria with increasing inlet velocity with the scale factor, the fuel and air supply pressure should be considered as a constrain when scaling up with large scale factor.

Keywords: Moderate or intense low-oxygen dilution (MILD) combustion, Natural gas, Scaling criteria, Computational fluid dynamics (CFD), NOx emission

1. Introduction

Moderate or intense low-oxygen dilution (MILD) combustion (Cavaliere and Joannon, 2004) is an interesting technology for modern thermal generation plants. It delivers high combustion efficiency as well as low NOx emission. This could be achieved by mixing the incoming air with recirculated hot flue gas prior to reacting with fuel under mixing controlled condition. Usually, high jet velocity of oxidizer is introduced to create enough entrainment of hot recirculating gas. This hot flue gas gets diluted with air mixture and further reacts with fuel downstream, creating a stable, well-distributed reaction zone in the combustion chamber. Consequently, the hot spot which promotes thermal NOx formation can be minimized while maintaining relatively more uniform radiative heat transfer from hot gas to the furnace wall. Because of widespread reaction without hot spot of intense reaction, it is also called “flameless oxidation” (FLOX) (Wünnin and Wünnin, 1997) or flameless combustion (Mancini et al., 2007). Due to high temperature of diluted oxidizer, it is also called “high temperature air combustion” (HiTAC) (Tsuji et al., 2003). Since the reaction zone in this combustion mode is colourless and spread widely in the combustion chamber, it was also named as “colourless distributed combustion” (CDC) (Arghode et al., 2010).

There have been several studies on MILD combustion, both experimentally and numerically, such as; effects of geometry and operating condition, the effect of burner configuration (Nada et al., 2015; Lee et al., 2019a), furnace chamber configuration (Schaffel-Mancini et al., 2010; Tu et al., 2015a), jet velocity of reactant (Mi et al., 2011; Verissimo et al., 2013), reactant temperature (Khoshhal et al., 2011; Huang et al., 2014), chemical composition of fuel and oxidizer (Dally et al., 2004; Tu et al., 2015b; Lee et al., 2019b), on NOx formation and reduction (Wünnin and Wünnin, 1997; Mancini et al., 2002) and microscopic characteristics (Jin and Zhou, 2015; Zhang et al., 2019).
Another important performance aspect of MILD combustion is the effect of scaling. When there is a desire for scaling up the unit from a laboratory-scale model to a full-scale prototype, there is a need in considering effects taking place with the change in geometry size on its combustion performance and emission. Ideally, scaling criterion should provide similar combustion and emission performance with the original model. However, it is not possible to find a universal scaling criterion of that capacity since combustion involves interaction of many complex processes that relate differently with the furnace, burner oxidizer and fuel inlets geometries as well as the operating conditions. On the other hand, it had been well-established that the recirculating gas with high temperature and its low oxygen content played an important role on MILD combustion. Some questions remain unanswered on how the change in geometry and burner size as well as the inlet velocity associated with different scaling criteria would affect to performance of MILD combustion, especially on NO\textsubscript{x} formation mechanism. It is therefore interesting to find out how different scaling criterion would affect to this important characteristic.

Many works in the past concern with studies on the effect of scaling on conventional burner; i.e. on a natural gas swirl burner (Weber, 1996; Hsieh et al., 1998; Orsino and Weber, 2000), pyrolysis fuel dump combustor (Cole et al., 2000), pulverized coal swirl burner (Weber, 1996; Weber and Breussin, 1998). However, effects of scaling under MILD condition has remained largely unexplored. One of significant research finding was given by Kumar et al. (2005). They proposed that the percentage of hot gas recirculation was an important factor for successful scaling up for MILD combustion. In their work, experiment and computational simulation was carried out at thermal throughput scale factor of up to 50. For dimensional (D) scaling, they had adopted $D \approx Q^{1/3}$ where $Q$ is the thermal throughput scale. The fuel velocity ($U_f$) scaling also followed $U_f \approx Q^{1/3}$ making the jet velocity to be very high at large scale. However, the air velocity was limited up to 100 m/s for practical reason. It appeared that the constant resident time (CRT) approach could maintain the heat release rate per unit volume while constant velocity (CV) approach would attenuate it when the burner was scaled up. A decrease in recirculation rate would be affected at greater degree when CV scaling was adopted. Therefore, CRT was favorable as far as scaling up of MILD combustion was concerned. Following this scaling requirement, an increase in gas injection velocity could be done on fuel side up to the limit of the supply pressure. Difficulties existed on the air supply side, however, when they attempted for practical scaling up to the industrial level. Therefore, scaling up of the air supply side was relaxed from CRT approach and compensated by an increase in jet velocity of the fuel side.

Another study on a laboratory-scale model on flameless mode of oxy-fuel combustion and its scaled-up version was recently published by Ghadamgahi et al. (2018). It was reported that the furnace had been successfully scaled up to the industrial level and the investigation was successfully carried out using validated computational fluid dynamics (CFD) model. That study had focused on data acquisition method. However, the effect on its performance due to change in geometry and thermal throughput was not reported.

The study on the effect of different scaling criteria, especially constant velocity and constant residence time approaches, on performance of MILD combustion has been relatively rare when compared to other performance aspects mentioned earlier. In addition, the study carried out by Kumar et al. (2005) was on a high heat release burner ($\approx 5.6$ MW/m\textsuperscript{3} of the combustion chamber), while another category of burner with relatively lower heat release has not been investigated. With this latter category, the design constrain is different from the former one as it allows larger space for flue gas mixing as well as the difference in utilization of thermal energy.

From existing literatures, factors affecting the burner’s performance as well as NO\textsubscript{x} emission has been extensively investigated. Although most of the past work had revealed the effect on NO\textsubscript{x} emission when scaling up with CV and CRT criteria, the effect under MILD condition had not been investigated so far. Due to such limited information regarding the effect of scaling on performance of MILD combustion for industrial combustor (0.023 MW/m\textsuperscript{3} of the base case), this work aimed at assessment on this burner category which have not been investigated so far. A comparison study was carried out on a semi-industrial, 0.58 MW model and its scale-up versions of 5.8 MW under two scaling approaches, the constant velocity and the constant residence time. CFD was carefully adopted as a tool for this assessment where flow aerodynamics, reaction, temperature distribution and NO\textsubscript{x} emission were reported. The size of chemical flame, which is one of important features of MILD combustion, is also investigated. The results were also discussed in term of Damköhler number which was one of important characteristic of MILD combustion. It also focuses on the effect of different scaling criteria on NO\textsubscript{x} emission level. The formation of NO\textsubscript{x} will be analyzed in relation with change in burner throughput. To the author’s knowledge, this performance aspect has not been reported in any existing literatures.
2. Approach of this study

2.1 Scaling criteria

In this study, geometric similarity was maintained where thermal throughput was scaled up using two scaling criteria; i) the constant velocity and ii) the constant residence time. These two well-known approaches had been adopted for scaling up conventional swirl stabilized combustors and their effects on combustion performances had been assessed (Weber, 1996; Weber and Breussin, 1998; Orsino and Weber, 2000).

The thermal throughput of the burner is evaluated as follow:

\[ Q_b = K \rho_0 U_0 D_0^2 \]  

where \( K \) is a proportionality constant, \( \rho_0 \) is the inlet fluid density, \( U_0 \) is the characteristic burner velocity and \( D_0 \) is the burner diameter. By maintaining constant gas velocity at the burner exit (\( U_0 = \) constant), the relationship between the burner diameter and its thermal throughput is as follow:

\[ \frac{D_2}{D_1} = \left( \frac{Q_2}{Q_1} \right)^{1/2} \]  

where \( D_1 \) and \( D_2 \) stand for geometry dimension of original and scale up version, respectively, \( Q_1 \) and \( Q_2 \) stand for thermal throughput of original and scale up version, respectively. In order to keep flow residence time constant between its laboratory scale model and its full-scale prototype, the ratio between the burner diameter and the inlet velocity must be maintained (\( D_0/U_0 = \) constant). This leads to the following relationship:

\[ \frac{D_2}{D_1} = \left( \frac{Q_2}{Q_1} \right)^{1/3} \]  

2.2 Reference case for a study on effect of scaling in MILD combustion

A semi-industrial scale furnace of the International Flame Research Foundation (IFRF) (Weber et al., 1999, 2005) as seen in Fig. 1 was adopted in this work. Natural gas was fired at 0.58 MW throughput. The furnace has a cross-section area of 2 × 2 m² with 6.25 m in length. The burner comprises of; i) one vitiated air inlet locating at the center of the inlet plane having a diameter of 0.124 m, and ii) two fuel inlets locating at 0.28 m horizontally from the oxidizer inlet, each of which had an initial port diameter of 0.01 m, then stepping up to 0.05 m before the inlet plane. The exhaust port of 0.75 m in diameter located at the center of an exit plane. The temperature of oxidizer gas was raised up by a pre-combustor of lean burn natural gas and later mixed with pure oxygen. Eventually, the temperature of oxidizer at inlet was as high as 1300 °C, with 19.5% oxygen, 6.4% carbon dioxide, 15% water vapour, 59.1% nitrogen and 110 ppm (dry) NO\(_x\) by volume. There were seven transverse monitoring locations along the furnace axis (z axis) as seen in Fig. 1. The ratio of axial distance from the burner to the furnace length (z/Z) equals to 0.024, 0.0688, 0.1168, 0.2128, 0.328, 0.5152 and 0.7968.

2.3 Computational method

The numerical simulation in this work is of three-dimensional type. A quarter of the furnace was modelled to minimize computational time. The hexahedral cell type was chosen for meshing. There were 606270 cells as seen in Fig. 2. The composition by volume of natural gas was; 87.8% methane, 4.6% ethane, 1.6% propane, 0.5% n-butane and 5.5% nitrogen. The composition of 94.5% methane and 5.5% of nitrogen was adopted to reduce the complication of combustion model.

In this study, the constant velocity and constant residence time scaling criteria were chosen. The thermal throughput was scaled up to the industrial level of 5.8 MW, which equal to thermal scale factor of 10. The operating condition is given in Table 1.

Gambit meshing software (ANSYS Gambit 2.4, 2006) was used for construction of the furnace domain and meshing. The mesh file was then transferred to Fluent CFD software (ANSYS Fluent 6.3, 2006) to perform a combustion simulation. Steady-state models were used for conservation of mass, momentum, energy and species
transport. Turbulence was modeled together with the Reynolds-averaged Navier-Stokes (RANS) equations of momentum. The standard $k$-$\varepsilon$ model was adopted as it provided stable and accurate solution for non-swirling flow and provided reasonable entrainment rate for oxidizer stream (Kim et al., 2008; Tu et al., 2015a). Standard wall function was adopted for modelling of turbulence near wall. The combustion of natural gas was modelled by the Eddy Dissipation Concept (EDC) which was proven to be suitable for MILD combustion (Vascellari and Cua, 2012; Lupant and Lybaert, 2015). The model was coupled with the four-step chemical reaction and seven chemical species as shown in Table 2. The radiation model used was P-1 model which had been widely used for MILD combustion (Vascellari and Cua, 2012; Tu et al., 2015a). The weighted sum of gray gas model (WSGGM) (Smith et al., 1982; Coppalle and Vervisch, 1983) was adopted for calculation of radiation absorptivity of gas mixture in the combustion domain.

The calculation method for formation of nitric oxide of nitrogen ($\text{NO}_x$) was done after the solution was converged (post-processing method). Since $\text{NO}_x$ concentration was relatively low compared with other major gas species, thus its effect to combustion was regarded as neglectable. $\text{NO}_x$ models in this study comprised of; Thermal $\text{NO}_x$ (Zeldovich et al., 1947), Prompt $\text{NO}_x$ (Fenimore, 1971) and $\text{NO}_x$ reduction (Kandamby et al., 1996). Detailed explanation of these models is available in Fluent (ANSYS Fluent 6.3 Theory Guide, 2006).

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![Fig. 1 The IFRF semi-industrial scale furnace and measuring transverse locations (dimension in m).](image1)

![Fig. 2 Computational domain and mesh of the furnace.](image2)
Table 1 The furnace parameter in different scaling approaches.

| Parameter                              | Semi-industrial scale | CV full industrial scale | CRT full industrial scale |
|----------------------------------------|-----------------------|--------------------------|---------------------------|
| Thermal throughput scale factor        | 1                     | 10                       | 10                        |
| Fuel thermal throughput                | 0.58 MW               | 5.8 MW                   | 5.8 MW                    |
| Oxidizer thermal input                | 0.35 MW               | 3.5 MW                   | 3.5 MW                    |
| Total thermal input                   | 0.93 MW               | 9.3 MW                   | 9.3 MW                    |
| Fuel inlet                            | 0.013056 kg/s         | 0.13056 kg/s             | 0.13056 kg/s              |
| Oxidizer inlet                        | 0.23056 kg/s          | 2.3056 kg/s              | 2.3056 kg/s               |
| Fuel inlet velocity                   | 123 m/s               | 123 m/s                  | 264 m/s                   |
| Oxidizer inlet velocity               | 87 m/s                | 87 m/s                   | 188 m/s                   |
| Geometry scale factor                 | 1                     | 3.1623                   | 2.1544                    |
| Fuel inlet diameter                   | 0.01 m                | 0.031623 m               | 0.021544 m                |
| Oxidizer inlet diameter               | 0.124 m               | 0.39213 m                | 0.26715 m                 |
| Fuel inlet residence time (theoretical)| 81 µs                | 257 µs                   | 81 µs                     |
| Oxidizer inlet residence time (theoretical) | 1425 µs       | 4507 µs                   | 1425 µs                   |
| Outlet diameter                       | 0.75 m                | 2.3717 m                 | 1.6158 m                  |
| Furnace length                        | 6.25 m                | 19.764 m                 | 13.465 m                  |
| Furnace width                         | 2 m                   | 6.3246 m                 | 4.3088 m                  |

Table 2 The global reaction mechanisms of natural gas combustion in the present study.

| Reactions                      | A (kmol/m³·s) | E (J/kmol) | Reaction orders | Reference                                      |
|-------------------------------|---------------|------------|-----------------|-----------------------------------------------|
| CH₄ + 0.5O₂ → CO + 2H₂        | 4.4x10¹⁰     | 1.2553x10⁸ | [CH₄]⁰.⁵[O₂]¹.²⁵ | (Jones and Lindstedt, 1988)                   |
| CH₄ + H₂O → CO + 3H₂          | 3.1x10⁸      | 1.2553x10⁸ | [CH₄][H₂O]      | (Jones and Lindstedt, 1988)                   |
| CO + 0.5O₂ → CO₂              | 2.5x10⁸      | 6.6948x10⁷ | [CO][O₂]⁰.³[H₂O]²⁰.⁵ | (Hotell et al., 1965)                        |
| H₂ + 0.5O₂ → H₂O              | 7.9x10¹⁰     | 1.4645x10⁸ | [H₂][O₂]¹.⁵      | (Marinov et al., 1996)                       |

2.4 Mesh independent study and model validation

Mesh independent study was carried out for the 0.58 MW furnace so that the effect of mesh refinement was kept at minimum for all cases under this investigation. The results from the calculation with 606270 cells were compared with those from 1295965 cells, i.e. the axial velocity, flue gas temperature, oxygen and carbon dioxide concentrations. The difference of these profiles along the axial distance from the burner exit plane were small, as seen in Fig. 3. Therefore, the calculation with 606270 cells was chosen for all scaled-up cases in a study on the effect of scaling. The simulation was also validated against published experimental results of IFRF, cited by Orsino et al., (2001). As seen in Fig. 4, the predicted result was satisfactorily agreed with experiment. This gave us reasonable degree of confidence for our next study on effect of scaling on MILD combustion.

Fig. 3 Mesh independent test in axial velocity, temperature, O₂ and CO₂ along the center line of the furnace.
3. Results and discussions

3.1 Scale effect on flow field

Figure 5 illustrates the axial velocity for the original 0.58 MW furnace and the 5.8 MW furnaces of both scaling criteria. Despite of the same amount in fuel and oxidizer mass flow for each burner throughput, scaling up using CRT scheme requires smaller chamber size than the CV scheme, as reflected in the relationship between geometry and thermal throughput ratios, see Eqs. (2) and (3). The gas velocity for the case of CRT scaling was higher than the CV’s...
in order to keep the flow residence time equal to that of its original model. Therefore, higher convection due to an increase in jet velocity was presented for the scaled-up version with CRT scheme. Figure 6 shows similarity in path lines of flow between the original model at 0.58 MW and its scaled-up versions. This recirculated flue gas with low oxygen content then mixed with incoming fuel and consequently mixed with vitiated oxidizer at central region of the furnace. At this point, stability occurred when the temperature and oxygen content in oxidizer were sufficiently high to react with the fuel-rich flue gas mixture.

Fig. 5 Contour of the axial velocity (m/s) in the x-z plane (y = 0).

Fig. 6 Path lines of the gas flow colored by axial velocity (m/s) in the furnace.
3.2 Scale effect on temperature distribution

Figure 7 shows temperature distributions of the original 0.58 MW and its scaled-up versions using CV and CRT. This stronger convection of CRT scaled-up version helped spreading out the high temperature zone downstream resulting in a relatively more uniform temperature distribution. The central jet of CRT was able to carry high thermal energy deeper downstream, while temperature of the base case and its CV scaled-up version was similar. In other word, higher momentum of the jet in CRT scaled-up version resulted in greater penetration of the central jet when compared with the CV scaled-up version and the base case.

With the case of CRT scaled-up version, relatively wider zone of high temperature was observed. It is also useful to note here that the wall temperature of all cases was maintained at 1500 K. Although, the heat loss at wall relates differently with scaling factor and contribute to dissimilarity in flue gas temperature at outlet plane, simulation suggested little difference in the ratio of heat extraction at wall to heat input by being less than one percent among all three cases, as shown in Table 3.

| Energy                          | 0.58 MW | 5.8 MW CV | 5.8 MW CRT |
|--------------------------------|---------|-----------|------------|
| Reactant enthalpy input (MW)   | 0.090871| 0.90865   | 0.90844    |
| Enthalpy of combustion¹ (MW)   | 0.14819 | 1.4819    | 1.4819     |
| Total energy input (MW)        | 0.23906 | 2.3905    | 2.3903     |
| Wall heat extraction (MW)      | 0.14018 | 1.3906    | 1.3880     |
| Flue gas enthalpy outlet (MW)  | 0.10205 | 1.0145    | 1.0575     |
| Total energy out (MW)          | 0.24223 | 2.4051    | 2.4455     |

¹Calculated based on natural gas lower calorific value.

3.3 Scale effect on oxygen concentration

Figure 8 illustrates oxygen concentration of the base case and its scaled-up versions. The finding coincides with temperature distribution as discussed in earlier section, where wider region of low oxygen content was observed, indicating that the consumption rate and convection effect of CRT scaling were relatively higher than those from CV scaling. Relatively lower oxygen content was also found at the exit of the furnace in this case.

Dimensional analysis suggested that Kolmogorov eddy time scale ($\tau_k$) was maintained while length scale ($l_k$) varied
with $Q^{1/3}$ for the case of CRT scaling. However, $\tau_k$ varied with $Q^{1/2}$ as well as its length scale for CV’s, see Eq. (7) and Kumar et al., (2005). Under non-premixed condition as occurred in MILD combustion, the reaction rate in a scaled-up furnace under CRT scheme was similar to that of its original version, while lower rate was found in a scaled-up version under CV scheme, see Fig. 9.

3.4 Scale effect on the internal recirculation rate

Figure 10 shows the internal recirculation rate ($K_V$) for both scaling criteria. This parameter has been defined and introduced by Wünning and Wünning (1998) and is calculated as follow:

$$K_V = \frac{m_l}{m_a + m_f}$$

(4)
It is the mass ratio between the recirculated gas \( (m_e) \) to the mass of all inlet jets, which includes fuel \( (m_f) \) and oxidizer \( (m_a) \). The recirculated gas is induced upstream by fuel and oxidizer jets. This parameter indicates how much the amount of hot recirculated gas containing low oxygen concentration is entrained by the jets. The higher value of \( K_V \) the greater degree of dilution taking place on the jet stream thus higher mixture temperature is realized with this hot gas mixing. With this scenario, stability can be achieved while keeping temperature in the reaction zone low in order to minimize the formation of thermal NO\(_x\). From Fig. 10, the profiles of all cases are similar. The peak value of \( K_V \) for each case is seen at location around \( z/Z = 0.5152 \) with the maximum value of 6.3 for all cases. The value of \( K_V \) has further decreased to 3.0 at \( z/Z = 0.7968 \).

![Fig. 10 The internal recirculation rate along the normalized axial distance.](image)

Figure 11 illustrates the development from unstable flame into MILD combustion of a 0.58 MW model and its 5.8 MW CV and 5.8 MW CRT prototypes at locations \( z/Z = 0.024, 0.0688, 0.1168, 0.2128, 0.328 \) and 0.5152, respectively. At first, second and third monitoring locations, flame was classified as unstable according to Wünning and Wünning (1998). However, after getting enough entrainment of hot recirculating gas, it has developed to be in MILD mode from the fourth, fifth and sixth monitoring locations. At these latter monitoring locations, the values of \( K_V \) of the base case, 0.58 MW, as well as the scaled-up cases, 5.8 MW CV and 5.8 MW CRT, were almost similar. In addition, the 5.8 MW CRT yielded slightly lower value of \( K_V \). However, higher in area-weighted average flue gas temperature was observed for 5.8 MW, when scaling under CRT scheme, as compared to its original version. This confirms that up to the scaling factor of 10, the CV and CRT scaling approaches do not have significant effect to MILD combustion characteristics.

![Fig. 11 The operation zone of each normalized axial distance.](image)
3.5 Scale effect on MILD combustion regime

Since MILD combustion is in flameless mode, it is merely possible to visualize the flame. The oxidation mixture ratio ($R_O$) was firstly defined by Yang and Blasiak (2005). This parameter was later used by Li et al. (2013) and Tu et al. (2015). It is therefore adopted in this study to identify the chemical flame shape. $R_O$ is calculated as follow:

$$R_O = \frac{x_{O_2}}{x_{O_2} + 2x_{CH_4} + 0.5x_{CO} + 0.5x_{H_2}} \tag{5}$$

where $x_{O_2}$, $x_{CH_4}$, $x_{CO}$ and $x_{H_2}$ represent the mole fraction of oxygen, methane, carbon monoxide and hydrogen, respectively. The value of $R_O = 0$ denotes fuel rich gas without oxygen while $R_O = 1$ denotes the oxygen rich gas without fuel. The flame border was defined at the location where $R_O = 0.99$ was presented (Yang and Blasiak, 2005). Figure 12 illustrates chemical flame border for all scaled-up furnace. It was found that the coverage of chemical flame with CRT scaling scheme was greater than that of the CV, indicating wide-spread flame with stronger convection effect created by higher jet velocity.

To investigate volumetric combustion, Yang and Blasiak (2005) had proposed a parameter so-called “Chemical flame occupation degree”, $R_F$, defined as follow:

$$R_F = \frac{V_f}{V_F} \tag{6}$$

where $V_f$ is the chemical flame volume (volume which the value of $R_O$ between 0 to 0.99) and $V_F$ is the furnace volume. From Fig. 12 it was found that the chemical flame volume of the CRT prototype occupied larger portion of the furnace space than its counterpart, the CV prototype, as well as its original model. Figure 13, showing the chemical flame occupation degree ($R_F$), suggests that the CRT scale up had 6.6%, while the base case and the CV prototype had 4.7%.

![Fig. 12 Iso-surface of $R_O = 0.99$ coloured by temperature (K).](image1)

![Fig. 13 Chemical flame occupation degree for the three cases.](image2)
MILD combustion possesses the magnitude of flow time scale being comparable to that of chemical time scale (Wang et al., 2018) or the former was one order of magnitude larger (Zhang et al., 2019). Damköhler number is the ratio of flow time scale ($\tau_f$) to reaction time scale ($\tau_c$) ($Da = \tau_f/\tau_c$). In this study $\tau_f$ is defined as the Kolmogorov time scale ($\tau_k$) calculated as follow:

$$\tau_k = \left(\frac{\nu}{\epsilon}\right)^{1/2}$$

where $\nu$ is the turbulent kinematic viscosity and $\epsilon$ is the turbulent dissipation rate. For $\tau_c$, in this study, it is calculated as follow:

$$\tau_c = \frac{C_{O_2} M_{O_2}}{R_{O_2}}$$

where $C_{O_2}$, $M_{O_2}$ and $R_{O_2}$ stand for molar concentration, molecular weight and net reaction rate of oxygen, respectively.

The flow time scale of the CV version was significantly greater than its original model and related with a square root of thermal throughput. However, in Fig. 14, the profile of $Da$ at different normalized transverse locations suggested slightly difference in magnitude between the base case and its scaled-up cases, with the profile of CRT spreading wider as seen at locations $z/Z = 0.0688, 0.1168$ and $0.2128$. This could be postulated that the chemical time scale also varied with thermal throughput at the same order with the flow time scale, although there was a slightly difference in $Da$ when compared with the base case of 0.58 MW.

Fig. 14 The Damköhler number along the normalized radial distance at different transverse locations.

### 3.6 Scale effect on NO\textsubscript{x} emission

Figures 15 and 16 indicates the effect of scaling criteria on NO\textsubscript{x} emission. Scaling up with CV criterion had led to significant increase in NO\textsubscript{x} emission, while CRT criterion yielded similar value with the original model with slightly lower emission (at 1.84% lower). Higher NO\textsubscript{x} concentration was clearly observed downstream of the furnace scaled-up with CV criterion. An increase in residence time under CV scaling up regime had played an important role on higher NO\textsubscript{x} emission. The detailed discussion on contribution of thermal NO\textsubscript{x}, prompt NO\textsubscript{x} and reduction of NO\textsubscript{x} (NO\textsubscript{x}12)
reburning) is given below.

Table 4 summarizes the contributions of thermal NO\(_x\), prompt NO\(_x\) and NO\(_x\) reburning on total emission. It was clear that thermal NO\(_x\) was the main contributor on NO\(_x\) emission followed by prompt NO\(_x\). Not surprisingly, as reburning NO\(_x\) mechanism was driven by the concentration of NO\(_x\) and HCN, the maximum NO\(_x\) reduction was found for the case scaled up with CV criterion. When scaling up using CV approach, it allows NO\(_x\) formation activity a longer residence time thus resulting in greater accumulation of NO\(_x\) in the furnace domain which eventually lead to higher NO\(_x\) emission. The result shows that thermal NO\(_x\) accumulation for the CV case was the highest (296.23 - 110 = 186.23) as compared with prompt NO\(_x\) with one order of magnitude lower (122.28 - 110 = 12.28).

![Fig. 15 NO\(_x\) concentration (ppm, volume dry) in the x-z plane (y = 0).](image1)

![Fig. 16 Outlet NO\(_x\) concentration for the three cases.](image2)
4. Conclusion

The effect of scaling criteria on performance of combustion when scaling up a semi-industrial scale MILD combustion to an industrial scale prototype has been numerically investigated. The constant velocity scaling and constant residence time scaling were employed to enhance the thermal throughput from the original semi-industrial scale furnace, 0.58 MW, by a factor of 10. It was found that by adopting conventional CV scaling criteria, an increase in NO\textsubscript{x} emission was observed. This work also presents the chemical flame occupation degree, $R_F$, the internal recirculation rate, $K_V$, and Damköhler number. Variations of these important indicative parameters across different scaling approaches were presented for the first time, when effects of scaling on the performances of MILD combustion were investigated. The main findings of this research are as follow.

1. MILD combustion could be scaled up satisfactorily with thermal scale factor of up to 10. When comparing the result of the base case and both of its scaled-up versions, the ratio between the recirculated mass to the mass of all inlet jet, $K_V$, was maintained at the same normalized location. This is an essential indicative parameter of MILD combustion.

2. The CV scaling criterion had resulted in longer flow residence time in the scaled-up version. However, mixing due to turbulence was less intense at the same order with flow residence time, resulting in similarity in flow aerodynamics. As for the CRT scaling approach, an increase in flow velocity led to higher turbulent intensity in the scaled-up version of the furnace, higher jet velocity was also observed at the same order with turbulence intensity, resulting in similarity in flow aerodynamics.

3. The chemical flame occupation degree of a furnace scaled-up with CRT scheme was relatively greater than its counterpart, the CV scaled-up version.

4. Similarity in distribution of Damköhler number was found among the base case and its scaled-up version of both scaling criteria with slightly wider distribution observed for CRT case. This is an indication of similarity in combustion where the ratio of flow time scale to the reaction time scale was maintained.

5. NO\textsubscript{x} emission of CV scaled-up case was, however, higher than its counterpart, the CRT’s, due to higher residence time of NO\textsubscript{x} formation under a kinetically controlled environment.

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