Domestic Range Burner Design Procedure

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ABSTRACT
This work describes the design procedure for domestic range burners. This is done keeping in mind that this burner has to maintain its stability under lateral air gusts, flame flashback is not allowed and if this happens, the flame has to return to its initial position within a maximum given time interval. Flame liftoff is not allowed either and CO emission has to be kept within legal acceptable limits. This procedure obeys the Brazilian Technical Specifications NBR 13723-1 and NBR 13723-2 issued by ABNT (Brazilian Society of Technical Norms)

Keywords: ovens, burners, domestic ranges

1 INTRODUCTION
The design and development of burners for domestic gas cooking devices (ranges) occupy a relevant part of the existing general burner design and development techniques. This family of burners attends not only the needs of ranges, but also they are used in domestic boilers as well as in situations needing the use of similar devices. These burners generate laminar partially pre-mixed flames. Therefore it will be employed here the corresponding theory along with existing correlation for flame length estimates. The part related to the combustion aerodynamics it is common the use of the approaches of Thring and Newby or of Craya and Curtet as described in Reference [1]. Here preference will be given to the work of the former authors, thanks to its greater simplicity and wide range of use under existing design conditions for this kind of burners.

It is expected that the present design will fully comply with the rules and constraints of specifications NBR 13723-1 [2] and NBR 13723-2 [3] of ABNT – Brazilian Society of Technical Norms.

2 DESIGN PROCEDURE AND NEEDED EQUATIONS
Domestic range burners fit three power ranges:

1) Burner nominal power ≤ 2.25 kW, design precision must be $\pm 8\%$

2) 2.25 kW $\leq$ Burner nominal power ≤ 3.6 kW, design precision must be ± 0.177 kW (i.e., within the 5-8% range)

3) Burner nominal power, ≥ 3.6 kW , design precision must be $\pm 5\%$

2.1 STEP 1: POWER ASSESSMENT
Therefore the first step of the burner design is the assessment of its power. Once this is accomplished, one must proceed as follows:

2.2 STEP 2 : CHOOSING OF THE WORKING REGION
Apply the power dissipation limit per unit area of each hole or slot. This limiting energy flux is displayed in Figures 1(a) and 1(b), for natural and manufactured gas, respectively. This limit implies that burners to be properly designed must display characteristics which will keep them inside the areas shown in those Figures. The total hole/slot area is:

$$A_{tot} = \frac{N \pi D^2}{4} \tag{1}$$

where N is the total number of holes (or slots) and D is their equivalent mean diameter. One also may write

$$\frac{\dot{m}_F \Delta h_c}{A_{tot}} = \frac{Power}{A_{tot}} = (x) \quad \frac{Watt}{mm^2} \tag{2}$$

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where the total area, A_{tot} (mm^2), is the sum of the areas of all holes and/or slots corresponding to the burner and $\dot{m}_F$ and Δh_C are the fuel mass flow rate and heat of combustion, in kg/s and J/kg, respectively. Hence,

$$ND^2 = \frac{4(Pwr)}{(x)\pi} \; [mm^2] \tag{3}$$

Next one chooses (in a somewhat arbitrary fashion), a value for N (or D) and then calculate D (or N) as the beginning of the project first loop recalling that ND^2 is given in mm^2
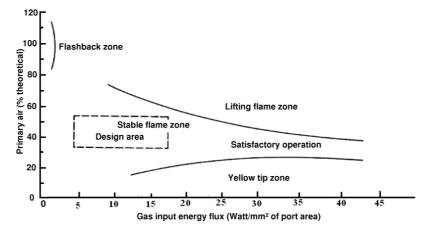

Figure 1(a) – Stability Diagram for Natural gas Flames, displaying flashback, liftoff and yellow tipping(*) zones along with proper design region for a burner consisting of a single row of circular holes (2.7 mm in diameter, spaced 6.35 mm). Taken from Reference [4]
(*) - Yellow tipping flame is an indication of soot formation within the flame
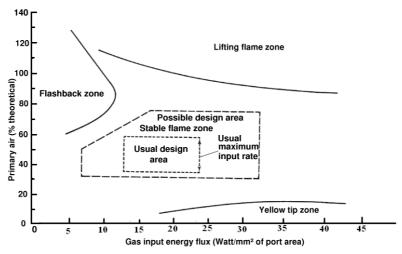

Figure 1(b) – Stability Diagram for Manufactured Gas Flames, displaying flashback, liftoff and yellow tipping(*) zones along with proper design region for a burner consisting of a single row of circular holes (2.7 mm in diameter, spaced 6.35 mm). Taken from Reference [4]
(*) - Yellow tipping flame is an indication of soot formation within the flame

Notice that upon choosing the hole diameter and/or the slots area one has to keep in mind the quenching distance and flashback limits as shown in Table 1. Also recall that the quenching diameter, d_T of a particular gaseous mixture is the minimum internal diameter of a pipe through which a flame in a stationary gas mixture can propagate. The quenching distance, d_0, is related to d_T and refers to the flame propagation between parallel plates (see Table 2). These parameters are related by the expression: $d_T = 1.54 \, d_0$ [5]

2.3 STEP 3: CALCULATING $\dot{m}$, THE TOTAL MASS FLOW RATE

The chosen total design heating power, $\dot{Q}$, leads to the mass flow rate, $\dot{m}$. Recalling that

$$\dot{Q} = \dot{m}_F \Delta h_c \tag{4}$$

Where $\dot{m}_F$ is the fuel mass flow rate and Δh_c is its high heating value.

Table1 – Flammability limits, quenching distances and minimum energy required for
ignition of several Fuels. Taken from Reference [4].

Fuel	Flammability limits			Quenching distance		Min. energy ignition	
	Φ_{min} (lean)	Φ_{max} (Rich)	Stoich. (A/F)$_{mass}$	For $\Phi=1$ (mm)	Absolute minimum	For $\Phi=1$ (10^{-5}J)	Abs. min. (10^{-5}J)
Acetylene, C_2H_2	0.19 [b]	∞ [b]	13.3	2.30	-	3.00	-
Carbon Monoxide CO	0.34	6.76	2.46	-	-	-	-
n-Decane $C_{10}H_{22}$	0.36	3.92	15.0	2.10 [c]	-	-	-
Ethane C_2H_6	0.50	2.72	16.0	2.30	1.80	42.0	24.0
Ethylene C_2H_4	0.41	> 6.10	14.80	1.30	-	9.60	-
Hydrogen H_2	0.14 [b]	2.54 [b]	334.5	0.64	0.61	2.00	1.80
Methane CH_4	0.46	1.64	17.2	2.50	2.00	33.0	29.0
Methanol, CH_3OH	9.48	4.08	6.46	1.80	1.50	21.5	14.0
n-Octane C_8H_{18}	0.51	4.25	15.1	-	-	-	-
Propane C_3H_8	0.51	2.83	15.6	2.00	1.80	30.5	26.0

a – Barnett, H. C., and Hibbard, R. R., (eds.), "Basic Considerations in the Combustion of
Hydrocarbon Fuels with Air," NACA Report 1300, 1959.
b – Zabetakis (U. S. Bureau of Mines, Bulletin 627, 1965).
c – Chomiak, J., Combustion: A Study in Theory, Fact and Application, Gordon & Breach,
NewYork, 1990.

Table 2 – Quenching Distances for Flames of several stoichiometric Mixtures
at 101 kPa and 293K [4]

Reactants	d_0 (mm)	Reactants	d_0 (mm)
$H_2 + O_2$	0.20	$H_2 + air$	0.60
$CH_4 + O_2$	0.30	$CH_4 + air$	2.50
$C_{2+}O_2$	0.20	$C_2H_2 + air$	0.50
$C_2H_4 + O_2$	0.10	$C_2H_4 + air$	1,25
$C_3H_8 + O_2$	0.25	$C_3H_8 + air$	2.10
$C_6H_6 + air$	1.90	$C_8H_{18} + air$	2.60

The air to fuel pre mixed mass ratio allows the calculation of the air mass flow rate .

$$\dot{m}_{air,pre} = \eta (A/F)_{stoich} \dot{m}_F \qquad (5)$$

where $(A/F)_{stoich}$ is the stoichiometric air to fuel mass ratio and η is the primary air fraction of the theoretical air (i.e., the ordinate in figures 1a or 1b divided by 100). Hence the total volumetric flow rate is

$$Q_{tot} = \frac{(\dot{m}_{air,pre} + \dot{m}_F)}{\bar{\rho}} \qquad (6)$$

$\bar{\rho}$ may be obtained using the ideal gas law with the mean molecular weight calculated for the air - fuel mixture:
The air pre-mixture mole fraction, $X_{air, pre}$, can be written as

$$X_{air,pre} = \frac{N_{air}}{N_{air} + N_F} = \frac{Z}{Z+1} \tag{7}$$

where Z is the Air/Fuel molar ratio, N_{air} and N_F are the air and fuel number of moles in the pre-mixture, respectively. Obviously, the fuel pre-mixture mole fraction, $X_{F,pre}$ is $X_{F,pre} = 1 - X_{air,pre}$ so that the pre-mixture Molecular weight, MW_{mix}, can be written as

$$MW_{mix} = X_{F,pre}(MW_F) + X_{air,pre}(MW_{air}), \tag{8}$$

where MW_{air} is usually taken to be equal to 28.85 g/mole. Hence $\quad \bar{\rho} = \dfrac{P}{\left(\dfrac{R_u}{MW_{mix}}\right)} \tag{9}$

2.4 STEP 4: FLAME SIZE LIMITS VERIFICATION

Assuming a uniform volumetric flow rate distribution among the existing holes/slots, then one may write Q slots/hole, as:

$$Q_{slot/hole} = Q_{tot}/N \tag{10}$$

and S, defined as the stoichiometric ratio between the number of moles of the ambient fluid and the number of moles of the nozzle fluid, i.e., S is the molar stoichiometric oxidizer-fuel ratio,

$$S = \left(\frac{\text{moles ambient fluid}}{\text{moles nozzle fluid}}\right)_{stoic} \quad \text{so that S can be written as } S = \frac{1 - \varphi_{pre}}{\varphi_{pre} + (1/S_{pure})} \tag{11}$$

where φ_{pre} is the fraction of the stoichiometric requirement met by the primary air, i.e., the primary aeration, and S_{pure} is the molar stoichiometric ratio associated with the pure fuel.

If all holes are circular then the following expression can be used to calculate the length of each individual flame, L_f (m)

$$L_f = 1330 \frac{Q_F(T_\infty/T_F)}{\ln(1+1/S)} \tag{12}$$

where Q_F, T_∞ and T_F are the fuel volumetric rate through a hole or slot and the fuel and ambient temperatures, respectively and all parameters are in SI units. However, if the unburnt gaseous exit holes have other shapes, proper equations, both theoretical and empirical, taken from Reference [4] can be found in Table 3

Table 3 – Theoretical and empirical correlations to estimate the vertical length of laminar flames [4]

Burner Geometry		Conditions	Applicable Equation
◯	Circle	Momentum or Buoyancy controlled	Circular – Eqns. 13 and 14
▭	Square	Momentum or Buoyancy controlled	Square - Eqns. 15 and 16
▭	Slot	Momentum controlled Buoyancy controlled Mixed momentum-buoyancy controlled	Eqns. 17 and 18 Eqns. 21 and 22 Eqn. 25

Note: For circular and square geometries the above suggested equations are applied to stationary oxidizer flow and co-flow. For slot geometry, equations can be applied for stationary flow only.

The following expressions can be used to estimate the flame vertical length for square and circular section burners. These results are valid regardless of buoyancy importance. They can also be used for fuel jets impinging into a quiescent atmosphere or in co-stream, if there is excess oxygen, i.e., if the flame is super ventilated. Then, for circular burners one may use

$$L_{f,th} = \frac{Q_F(T_\infty/T_F)}{4\pi D_\infty \ln(1+1/S)}\left(\frac{T_\infty}{T_f}\right)^{0,67} \tag{13}$$

$$L_{f,exp} = 1330 \; \frac{Q_F(T_\infty/T_F)}{\ln(1 + 1/S)} \tag{14}$$

where S the molar stoichiometric oxidizer-fuel ratio defined above, D_∞ is a mean diffusion coefficient evaluated for the oxidizer at the oxidizer stream temperature, T_∞, T_F and T_f are the ambient, the fuel stream and the mean flame temperatures, respectively. All parameters in Equations (13) and (14) are in SI units. Notice that the burner port diameter does not appear explicitly in these equations.

2. 4. 1 SQUARE PORT BURNERS
Here the following expressions can be used (Ref [4])

$$L_{f,th} = \frac{Q_F(T_\infty/T_F)}{16 D_\infty [\text{inverf}(1+S)^{-0,5}]^2}\left(\frac{T_\infty}{T_f}\right)^{0.67} \tag{15}$$

and

$$L_{f,exp} = 1045 \frac{Q_F(T_\infty/T_F)}{[\text{inverf}(1+S)^{-0,5}]^2} \tag{16}$$

where inverf is the inverse error function (i.e., w = inverf (erf w), erf being the well known error function). Again, all quantities are evaluated in SI units.

2. 4. 2 SLOT PORT BURNER – MOMENTUM CONTROLLED (Ref [4])
For this kind of burner, the theoretical and experimental expressions for the flame length, $L_{f,th}$ and $L_{f,exp}$, respectively, can be written as

$$L_{f,th} = \frac{b\beta^2 Q_F}{hID_\infty Y_{F,stq}}\left(\frac{T_\infty}{T_F}\right)^2\left(\frac{T_f}{T_\infty}\right)^{0,33} \tag{17}$$

$$L_{f,exp} = 8{,}6\text{x}10^{-4}\frac{b\beta^2 Q_F}{hIY_{F,stq}}\left(\frac{T_\infty}{T_F}\right)^2 \tag{18}$$

where b is the slot width, h is the slot length as shown in Table 3 , $Y_{F,stq}$ is the fuel mass fraction for stoichiometry and the function β is given by

$$\beta = \frac{1}{4\text{inverf}[1/(1+S)]} \tag{19}$$

and I is the ratio of the actual initial momentum flow, $J_{e,real}$, from the slot to that of the uniform flow, i.e.,

$$I = \frac{J_{e,real}}{\dot{m}_F v_e} \tag{20}$$

If the flow is uniform, I = 1, and, for a fully developed parabolic exit velocity profile assuming h >> b, I = 1.5. Equations (17) and (18) apply only if the atmosphere is stagnant, otherwise one should use the results of References [6] and [7].

2. 4. 3 SLOT PORT BURNER – BUOYANCY CONTROLLED (Reference [4])
Now $L_{f,th}$ and $L_{f,exp}$ are given by

$$L_{f,th} = \left[\frac{9\beta^4 Q_F^4 T_\infty^4}{8 D_\infty^2 a h^4 T_F^4}\right]^{1/3}\left[\frac{T_f}{T_\infty}\right]^{2/9} \tag{21}$$

$$L_{f,exp} = 2\text{x}10^3\left[\frac{\beta^4 Q_F^4 T_\infty^4}{a h^4 T_F^4}\right]^{1/3} \tag{22}$$

where a is the mean buoyancy acceleration given as:

$$a \cong 0{,}6g\left(\frac{T_f}{T_\infty} - 1\right) \tag{23}$$

where g is the gravitational acceleration. Roper et al [7] used a mean temperature of 1500K to evaluate the acceleration. As it can be seen in Equations (21) and (22) the flame length is a weak function of a (-1/3 power)

2. 4. 4 TRANSITION REGIME

To verify if the flame is momentum or buoyancy controlled, the flame Froude Number Fr_f, has to be checked. Recall that the Froude number is defined as the ratio between the initial jet momentum flow rate and the buoyancy force experimented by the flame. Then for a laminar jet flowing into a stagnant atmosphere,

$$Fr_f \equiv \frac{(v_e I Y_{F,stq})^2}{aL_f} \tag{24}$$

Then the flow regime is characterized by the following criteria:

$F_{rf} \gg 1$ momentum controlled

$F_{rf} \approx 1$ transition

$F_{rf} \ll 1$ buoyancy controlled

Notice that for a given flow regime is to be established, a value has to be assigned for L_f. Hence a later check is needed to confirm if the chosen regime was the correct one

For the transition situation, where both the jet momentum and the flame buoyancy are important, Roper [6,7] suggests the following correlation:

$$L_{f,T} = \frac{4}{9} L_{f,M} \left(\frac{L_{f,B}}{L_{f,M}}\right)^3 \left\{ \left[1 + 3,38 \left(\frac{L_{f,M}}{L_{f,B}}\right)^3\right]^{2/3} - 1\right\} \tag{25}$$

where subscripts M, B and T stand for momentum controlled, buoyancy controlled and transition regime, respectively.

2. 5 STEP 5: DESIGN RELIABILITY CHECK

Check if the design is practical, i.e., if the chosen diameter or slot width fit in the burner allotted space, if the flame will propagate without any problems, if there will be no flashback and finally run CO emission (see Table 5) and lateral wind resistance tests and, if approved, confirm the overall efficiency and actual burner power.

Table 5 – Maximum (CO) allowed in combustion products [2,3]

Test Run	Burners in operation	Type of gas	Dial positioning (flow rate)	Testing Pressure	% max (CO)
1	Each burner individually	Reference gas	Maximum	Maximum	0.10 [2]
2	Each burner individually	Reference gas	Position corresp to ½ nominal rate	Nominal	0.15
3	Each burner individually	Gas on limit of Incomplete Combustion	Maximum	Maximum	0.15
4	All burners of table[1] plus, if possible, of oven and grill simultaneously, by radiation	Reference gas	Maximum	Maximum	0.20
(1) Simultaneous operation of oven and grill by radiation, if they are in different compartments. Successive operation if they are in the same compartment					
(2) For third group gases (see Table 6 below) the value is 0.15 %(CO)					

Tables 6 and 7 display the characteristics of the testing gases within three groups (families) and the pressures these families should be tested, respectively

2 . 6 STEP 6: PRE-MIXING PIPE DESIGN

Upon choosing the pre-mixing ratio according to figure 1 (a) or (b) it is noticed that, for the design to fall within the proper area, this ratio should be limited between 35% to 60% of the primary air flow rate

Therefore a pre-mixing design factor must be chosen and adopted in designing the upper section of the burner, so that the entrained portion of the primary air flowing into it, $\dot{m}_e$, will be known.

A general expression for estimating the fluid entrainment for jets of different, non-constant densities, used by Field et al. (1) is the one given by Ricou e Spalding [1, 8]

$$\frac{\dot{m}_e}{\dot{m}_o} = 0,32 \left(\frac{\rho_a}{\rho_0}\right)^{1/2} \frac{x}{d_0} - 1 \tag{26}$$

where $\dot{m}_0, d_0$, x, ρ_a and ρ_0 are the fuel mass flow rate, the gas admission orifice diameter, the distance taken along the central axis downstream the flow, the air density and the gas density at the throat, respectively. This way the length of the pre-mixing duct can be estimated. Figure 2 displays the schematics of concentric jets flow behavior similar to the one taking place in the pre-mixing tube of a conventional range burner. To calculate the distance from the jet origin (i.e., from the gas orifice) to point P, X_p, where the jet hits the wall tube: Choosing the jet spread semi-angle to be 9.7° one obtains

$$\frac{L}{X_P} = \tan 9.7° \quad \text{hence,} \quad X_p = 5.85\ L \tag{27}$$

where 2L is the tube diameter. Considering the primary and secondary flows as a single jet (i.e., $X_N = 0$),the distance from the throat to point C in Figure 2, may be given as:

$$X_1 = \frac{1}{2}\left[X_p + \frac{d_0'}{0.32}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \right] \tag{28}$$

where d_0' is the initial jet diameter

TABLE 6 – Testing gases characteristics [2,3]

Group	Testing gases	Designation	Composition (volume, %)	PCS[1] MJ/m³(kcal/m³)	Wobbe Index MJ/m³(kcal/m³)	Relative mass density (air=1)
First Group	Reference	G10	$H_2(37), CH_4(30), N_2(33)$	15.8(3773)	22.1 (5279)	0.511
	Incomplete combustion limit	G11	$H_2(38), CH_4(32), N_2(30)$	16.7 (3962)	23.7 (5668)	0.494
	Flame flashback limit	G12	$H_2(39), CH_4(27), N_2(34)$	14.9 (3561)	21.0 (5009)	0.505
SecondGroup	Reference and flame displacement limit	G20	$H_2(2), CH_4(88), C_3H_8(10)$	42.9 (10261)	53.6 (12801)	0.643
	Incomplete Combustion Limit	G21	$CH_4(81), C_3H_8(19)$	48.6 (11611)	56.5 (13494)	0.740
	Flame flashback limit	G22	$H_2(10), CH_4(85), C_3H_8(5)$	38.0 (9088)	51.1 (12203)	0.555
Third Group	Reference Incomplete combustion limit	G30	$C_4H_{10}(100)$	126.5 (340212)	87.6 (20938)	2.082
	Flame displacement limit	G31	$C_3H_8 (100)$	95.9 (22905)	77.0 (18388)	1.552
	Flame lifting limit	G32	$C_3H_6 (100)$	93.7 (22395)	77.9 (18600)	1.450
(1) Taken at 15° C and 101.33 kPa (1013.25 mbar) (2) Wobbe index taken at High Heating Value						

TABLE 7 – Testing pressures

Group	Normal pressure KPa	Minimum Pressure KPa	Maximum Pressure KPa
First Group	0.98	0.39	1.47
Second Group	1.96	1.47	2.45
Third Group	2.75	1.96	3.43

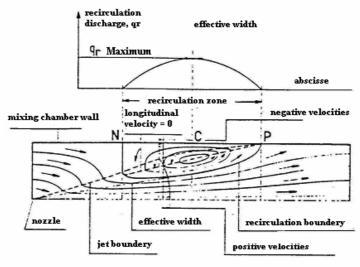Then introducing a parameter θ, (i.e., the Thring and Newby modified parameter [10]) such that

$$\theta = \frac{d_0'}{2L}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{29}$$

equation (28) may be written as

$$X_1 = \frac{1}{2}\left(X_p + \frac{2L\theta}{0.32} \right) = L\left(2{,}925 + \frac{\theta}{0.32} \right) \tag{30}$$

If $\dot{m}_e = \dot{m}_r$, the re-circulation mass flow rate, the flow rate entrained between the throat and point C is given by:

$$\frac{\dot{m}_e}{\dot{m}_0} = \frac{0.32}{\theta}\frac{X_1}{2L} - 1 = \frac{0.16}{\theta}\left(2.925 + \frac{\theta}{0.32}\right) - 1 = \frac{0.47}{\theta} - 0.5 \qquad (31)$$

strength and size of the "recirculation eddy" effect

Figure 2 – Map of the recirculation for a ducted axisymmetric jet (after M. Barchilon and R. Curtet , taken from Reference [1]

CONCLUSIONS
The design engineer following the above described steps will obtain a burner performing close to the imposed pre-requisites. From this point on the engineer will adequate the number of holes and/or slots, or both, following a pattern (round in general) so that the burner will comply with the CO (carbon monoxide) emission constraints. To achieve this, he has to take into account the interactions among the flames, so that the final result is shorter than the overall flame length initially established. In the same way, a better geometric arrangement of the unburned gases exit orifices will allow a better oxygen (air) feed to the flame, thus precluding the formation of the yellow tips typical of CO emission. Hence the flame aerodynamics is of utmost importance in domestic oven burners design.

ACKNOWLEDGEMENTS

REFERENCES
1. Beér, J. M. and Chigier, N. A., Combustion Aerodynamics –Applied Science Publishers, Essex,England, 1974
2. ABNT -Brazilian Society of Technical Norms, NBR 13723-1, Home cooking gas range, Part 1:Performance and safety, April 1999 (in portuguese)
3. ABNT -Brazilian Society of Technical Norms, NBR 13723-2, Home cooking gas range, Part 2: Rational energy comsumption, April 1999 (in portuguese)
4. Turns, S. R., An Introduction to Combustion, Concepts and Applications, 2nd Ed., McGraw-Hill. Inc., 2000.
5. Griffiths, J. F. and Barnard, J. A., Flame and Combustion, 3rd Ed. Blackie Academic &   Professiona1, 1995.
6. Roper, F. G., The prediction of Laminar Jet Diffusion Flame Sizes: Part I. Theoretical Model, Combustion and Flame, Vol.29, pp. 219-226, 1977.
7. Roper, F. G., Smith, C., and Cunningham, A. C., The prediction of laminar jet diffusion flame sizes: Part II, Experimental verification, *Combustion and Flame*, Vol.29, pp227-234, 1977.
8. Ricou, F. P.and Spalding, D. B., Measurements of entrainment by axisymmetrical turbulents jets. *J. Fluid Mech.,* Vol.11, pp.21-32, 1961.
9. Gas Engineers Handbook, The Industrial Press, New York, NY, 1966,