DOMESTIC RANGE BURNER DESIGN PROCEDURE

Heraldo da Silva Couto
couto@unifor.br

João Batista Furlan Duarte
furlan@unifor.br

Lutero Carmo de Lima
luterocl@unifor.br

Demétrio Bastos Netto
demetrio@lcp.inpe.br

Resumo

Este trabalho decreve os procedimentos de projeto de queimadores de fogão doméstico. Isto é feito tendo em mente que os queimadores devem obedecer a critérios técnicos, tais como: resistência a vento lateral, não deve permitir engolimento de chama. Se isso ocorrer, a chama deverá retornar à sua posição inicial dentro de um dado intervalo de tempo. Flutuação da chama não é permitida e a emissão de CO deve encontrar-se na NBR 13723-2 da ABNT (Associação Brasileira de Normas Técnicas).

Palavras-chave: *combustão, queimadores de mesa, comprimento de chama.*

Abstract

This work describes the design procedure for domestic oven burners. This is done keeping in mind that this burner has to keep 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*

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 ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (1999a). 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 ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (1999a) and ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (1999b).

DESIGN PROCEDURE AND NEEDED EQUATIONS

Domestic range burners fit three power ranges:

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

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

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

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

Step 2: 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.

The limit can be written as:

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

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,

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

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.

Therefore, $ND^2 \quad [\text{mm}^2]$ (4)

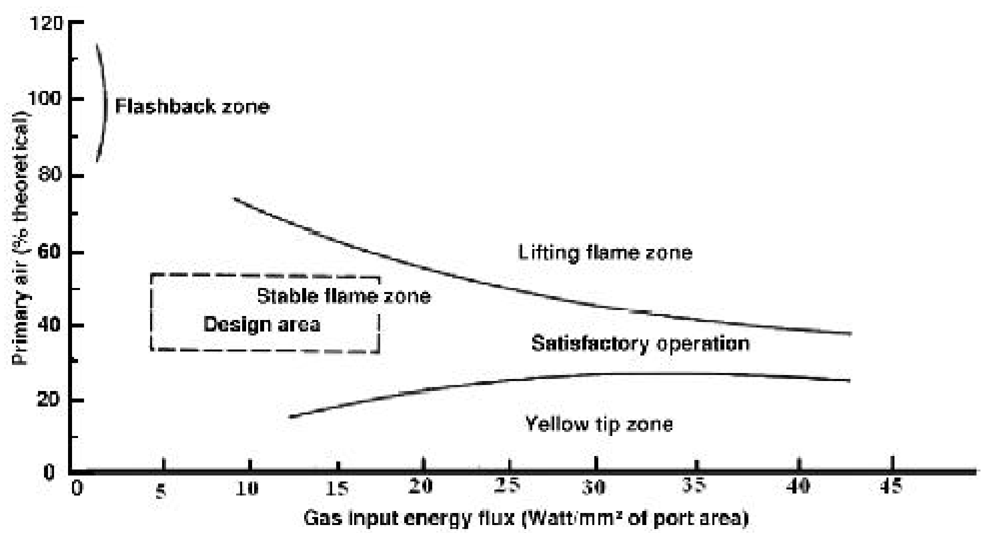

Figure 1(a) – Stability Diagram for Natural gas Flames, displaying flashback, liftoff and yellow tipping(*) zones along with proper design region for a burner consisting of a single row of circular holes (2.7 mm in diameter, spaced 6.35 mm). Taken from TURNS (2000).

(*) - 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:

Table1 – Flammability limits, quenching distances and minimum energy required for ignition of several Fuels. Taken from TURNS (2000).

	Flammability limits			Quenching distance		Min. energy ignition	
Fuel	Φ_{min} (lean)	Φ_{max} (Rich)	Stoich. $(A/F)_{mass}$	For Φ=1 (mm)	Absolute minimum	For Φ=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.

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: $d_T = 1.54\, d_0$ (GRIFFITHS and BARNARD, 1995).

Table 2 – Quenching Distances for Flames of several stoichiometric Mixtures at 101 kPa and 293K (TURNS, 2000).

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

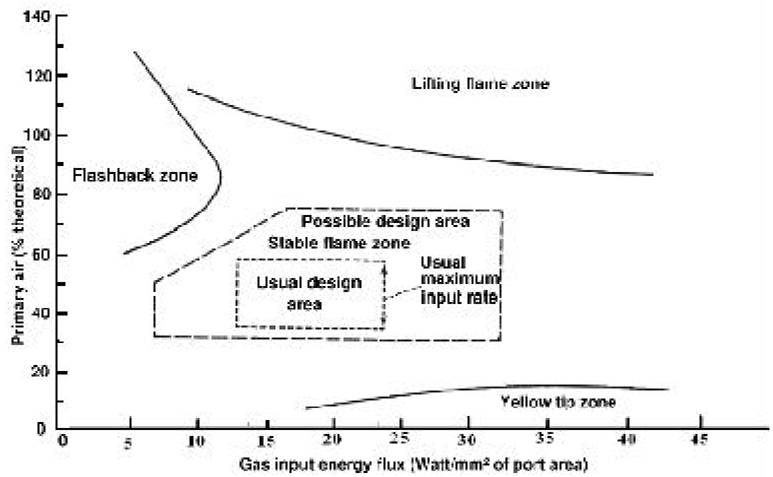

Figure 1(b) – Stability Diagram for Manufactured Gas Flames, displaying flashback, liftoff and yellow tipping (*) zones along with proper design region for a burner consisting of a single row of circular holes (2.7 mm in diameter, spaced 6.35 mm). Taken from TURNS (2000).

(*) - Yellow tipping flame is an indication of soot formation within the flame

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

$$\dot{Q} = \dot{m}_F \Delta h_c \tag{5}$$

Where $\dot{m}_F$ is the fuel mass flow rate and Δh_c is its high heating value. The air to fuel pre mixed mass ratio allows the calculation of the air mass flow rate

$$\dot{m}_{air,pre} = \eta \, (A/F)_{stoich} \dot{m}_F \tag{6}$$

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

$$Q_{tot} = \frac{(\dot{m}_{air,pre} + \dot{m}_F)}{\bar{n}} \tag{7}$$

$\bar{n}$ can 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

$$X_{air,pre} = \frac{N_{air}}{N_{air} + N_F} = \frac{Z}{Z+1} \tag{8}$$

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

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

where MW_{air} is usually taken to be equal to 28.85 g/mole. Hence

$$X_{ar,pri} = \frac{N_{ar}}{(N_{ar} + N_F)} = \frac{Z}{Z+1} \tag{8}$$

$$\bar{\tilde{n}} = \frac{P}{\left(\dfrac{R_u}{MW_{mix}}\right)} \tag{9}$$

Step 4 – Flame size limits verification.

Assuming a uniform volumetric flow rate distribution among the existing holes/slots, then one may write $Q_{slot/hole}$, 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,

$$S = \left(\frac{\text{moles ambient fluid}}{\text{moles nozzle fluid}}\right)_{stoic}$$

so that S can be written as

$$S = \frac{1 - \boldsymbol{j}_{pre}}{\boldsymbol{j}_{pre} + (1/S_{pure})} \tag{11}$$

where $\boldsymbol{j}_{pre}$ 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 TURNS (2000) can be found in Table 3.

Table 3 – Theoretical and empirical correlations to estimate the vertical length of laminar flames (TURNS, 2000).

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.

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

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

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.

SQUARE PORT BURNERS

Here the following expressions can be used (TURNS, 2000).

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

and

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

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.

SLOT PORT BURNER – MOMENTUM CONTROLLED (TURNS, 2000)

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

$$L_{f,th} = \frac{b\hat{a}^{2}Q_{F}}{hID_{\infty}Y_{F,stq}}\left(\frac{T_{\infty}}{T_{F}}\right)^{2}\left(\frac{T_{f}}{T_{\infty}}\right)^{0,33} \qquad (17)$$

$$L_{f,exp} = 8{,}6x10^{-4}\frac{b\hat{a}^{2}Q_{F}}{hIY_{F,stq}}\left(\frac{T_{\infty}}{T_{F}}\right)^{2} \qquad (18)$$

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

$$\hat{a} = \frac{1}{4\mathrm{inverf}[1/\ (1+S)]} \qquad (19)$$

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.,

$$I = \frac{J_{e,real}}{\dot{m}_{F}v_{e}} \qquad (20)$$

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 ROPER (1977) and ROPER, SMITH and CUNNINGHAM (1977).

SLOT PORT BURNER – BUOYANCY CONTROLLED (TURNS, 2000)

Now $L_{f,th}$ and $L_{f,exp}$ are given by

$$L_{f,th} = \left[\frac{9\hat{a}^{4}Q_{F}^{4}T_{\infty}^{4}}{8D_{\infty}^{2}ah^{4}T_{F}^{4}}\right]^{1/3}\left[\frac{T_{f}}{T_{\infty}}\right]^{2/9} \qquad (21)$$

$$L_{f,exp} = 2x10^{3}\left[\frac{\hat{a}^{4}Q_{F}^{4}T_{\infty}^{4}}{ah^{4}T_{F}^{4}}\right]^{1/3} \qquad (22)$$

where a is the mean buoyancy acceleration given as:

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

where g is the gravitational acceleration. ROPER, SMITH and CUNNINGHAM (1977) 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)

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,

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

Then the flow regime is characterized by the following criteria:

$$F_{rf} >> 1 \quad \text{momentum controlled}$$

$$F_{rf} \approx 1 \quad \text{transition}$$

$$F_{rf} << 1 \quad \text{buoyancy controlled}$$

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 (1977) and ROPER, SMITH and CUNNINGHAM (1977) 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.

STEP 4

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 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1999a,b)

Test Run	Burners in operation	Type of gas	Dial position (flow rate)	Testing Pressure	% maximum (CO)
1	Each burner individually	Reference gas	Maximum	Maximum	0.10 [2]
2	Each burner individually	Reference gas	Position corresponding 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

(1) 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.

Table 6 – Testing gases characteristics (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1999a,b)

Group	Testing gases	Designation	Composition (volume, %)	PCS(1) $MJ/m^3(kcal/m^3)$	Wobbe Index $MJ/m^3(kcal/m^3)$	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
Second Group	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

Step 5

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 (BEER and CHIGIER, 1974; RICOU and SPALDING, 1961).

$$\frac{\dot{m}_e}{\dot{m}_o} = 0,32\left(\frac{\tilde{n}_a}{\tilde{n}_0}\right)^{1/2}\frac{x}{d_0} - 1 \qquad (26)$$

where $\dot{m}_0, d_0$, x, $\tilde{n}_a$ and $\tilde{n}_0$ 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 9.7º one obtains

$$\frac{L}{X_P} = \tan 9.7^o$$

hence,

$$Xp = 5.85\ L \tag{27}$$

where 2L is the tube diameter.

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

$$X_1 = \frac{1}{2}\left[X_p + \frac{d_0'}{0.32}\left(\frac{\tilde{n}_0}{\tilde{n}_a}\right)^{1/2}\right] \tag{28}$$

where d_0' is the initial **jet diameter**

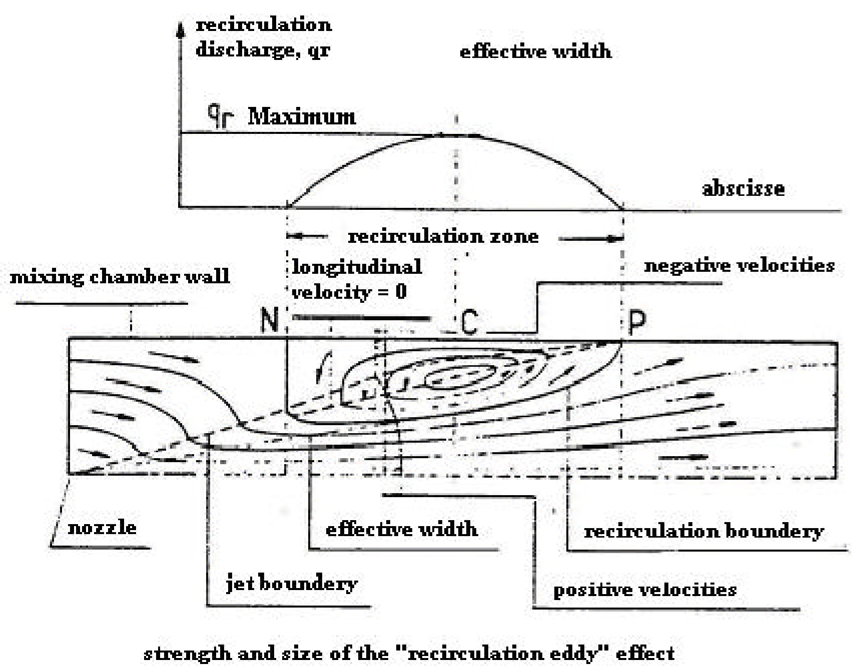

Figure 2 – Map of the recirculation for a ducted axisymmetric jet (BARCHILON and CURTET, 1964).

Then introducing a parameter θ, (i.e., the Thring and Newby modified parameter GAS, 1966) 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 recirculation mass flow rate, the flow rate entrained between the throat and point C is given by:

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

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

Part of this work was done under the sponsorship of the Brazilian National Research Council (CNPq), Project Numbers 501459/2003-0 and 350545/2002-2.

References

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 13723 – 1*: aparelho doméstico de cocção a gás: parte 1: desempenho e segurança. Rio de Janeiro, 1999.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 13723 – 2*: aparelho doméstico de cocção a gás: parte 2: uso racional de energia. Rio de Janeiro, 1999.

BARCHILON, M.; CURTET, R. J. Basic engineer. *ASME*, New York, v. 28, p. 777, 1964.

BEER, J. M.; CHIGIER, N. A. *Combustion aerodynamics*. Essex: Applied Science Publishers, 1974.

GAS engineers handbook. New York: The Industrial Press, 1966.

GRIFFITHS, J. F.; BARNARD, J. A. *Flame and combustion.* 3th ed. London: Blackie Academic & Professional, 1995.

RICOU, F. P.; SPALDING, D. B. Measurements of entrainment by axisymmetrical turbulents jets. *Fluid Mechanics*, Cambridge, v. 2, p. 21-32, 1961.

ROPER, F. G. The prediction of laminar jet diffusion flame sizes: part 1: theoretical model. *Combustion and Flame*, New York, v. 29, p. 219-226, 1977.

ROPER, F. G.; SMITH, C.; CUNNINGHAM, A. C. The prediction of laminar jet diffusion flame sizes: part 2: experimental verification. *Combustion and Flame*, New York, v. 29, p. 227-234, 1977.

TURNS, S. R. *An introduction to combustion, conceitos and applications*. 2th ed. New York: McGraw-Hill, 2000.

ABOUT THE AUTHORS

Heraldo da Silva Couto
Graduado em Física pela Pontifícia Universidade Católica de São Paulo – PUC – SP em 1977, Mestrado em Engenharia e Tecnologia Espaciais pelo Instituto Nacional de Pesquisas Espaciais – INPE, em São José dos Campos, São Paulo em 1982 e Doutorado em Engenharia Química pela Universidade Federal do Rio de Janeiro em 1989. Atualmente é professor da Universidade de Fortaleza.

João Batista Furlan Duarte
Graduado em Licenciatura Plena em Física pela Universidade Federal de Santa Maria, Rio Grande do Sul, em 1993, Mestrado em Física Computacional em 1995 pela Universidade Federal do Ceará e Doutorado em 1998 em Física Computacional pela Universidade Federal do Ceará. Atualmente é professor na Universidade de Fortaleza.

Lutero Carmo de Lima
Graduado em Física pela Universidade Santo Amaro, São Paulo em 1974, Mestrado em Engenharia Mecânica pela Universidade de Santa Catarina em 1979, Doutorado em Engenharia Mecânica pela Universidade de São Paulo em 1986 e Pós-Doutorado (Fulbright Scholar) no Clean Energy Research Institute da Universidade de Miami em 1991. Atualmente é professor de Física do Centro de Ciências e Tecnologia da Universidade Estadual do Ceará.

Demetrio Bastos-Netto
B.Sc. em Ciências Navais pela Escola Naval, M.Sc. em Engenharia Aeronáutica e Astronáutica pela University of Michigan, Ph.D. em Engenharia Aeroespacial pela University of Michigan, Pesquisador 1-A do CNPq, Chefe do Laboratório Associado de Combustão e Propulsão (LCP) do INPE, Presidente do Conselho de Pós-Graduação do INPE.