DEVELOPMENT OF A MICRO HEATING SYSTEM TO MANUFACTURE FIBER OPTIC TAPERS

Cemin, D., douglascemin@yahoo.com.br
Lima, J. A., dem2jasl@joinville.udesc.br
Santa Catarina State University.
Department of Mechanical Engineering.
Campus Universitário, Bom Retiro,Tel: (47) 4009-7900.
89223-100, Joinville-SC.

Paterno, A. S., dee2asp@joinville.udesc.br
Santa Catarina State University.
Department of Electrical Engineering.
Campus Universitário, Bom Retiro,Tel: (47) 4009-7981.
89223-100, Joinville-SC.

Abstract. *This paper presents an interesting application of combustion fundamentals in the development of a micro gas heater. Although the flame brush technique is well characterized, an important parameter is lacking: the appropriate volumetric flow rates of oxygen and butane. These are fundamental parameters to develop the heating system to manufacture fiber optic tapers. The authors report the experimental and theoretical methods used to determine such flow rates, and its values. By knowing these parameters a significant improvement was made in the heating system of the fiber optic taper rig implemented in the laboratory of instrumentation at the Santa Catarina State University, allowing the manufacture of fiber optic tapers of considerably reduced dimensions.*

Keyword: *Fiber optic tapers, flame speed, gas heater, flow rate.*

1. INTRODUCTION

Optical fiber consists of a cylindrical core with a refractive index slightly higher than the surrounding cladding refractive index, which results in light propagation by total internal reflection. Light propagating through an optical fiber consists of two components: the guided field in the core and the exponentially decaying evanescent field in the cladding. In uniform-diameter cladded fibers, light propagating cannot interact with the surroundings of the fiber because the evanescent field decays to almost zero within the cladding. In order to use optical fiber as a sensing element it requires light to interact with the surroundings of the fiber. One way to achieve this interaction is to expose the evanescent field of the transmitted light, and this can be exploited for atom guides, particle manipulation, sensors and high-Q resonators applications.

Several investigators have developed techniques to create large evanescent fields by bending, tapering, altering the light launching angle, or increasing the wavelength. Among these techniques, tapering has gathered enormous attention in the recent years. Tapering the optical fiber not only exposes the evanescent field to the surroundings, but also increases the evanescent field magnitude and its penetration depth. It was shown to enhance the potential of the optical fiber as a sensor and can be performed by removing the cladding and then tapering the core, or keeping both the core and cladding in place and tapering the entire fiber. A continuous tapered fiber consists of an optical fiber by gradually decreasing its diameter, which is formed by a constant-diameter waist region, which gradually increases back to the original diameter (Brambilla *et al.* 2009). Light enters a continuous taper from one extremity and is transmitted through the taper to the detector.

Fiber optic tapers can be made from a cylindrical silica fiber with a nominal diameter of 125 μm by heating a length of the fiber up to a softening point while slowly and adiabatically stretching it, reducing its physical diameter to a micro- or nano-metric order. The result is a continuous biconical taper comprising of the taper waist and two conical regions linked to the unstretched parts in both ends. The waist region is used as the sensing region because the evanescent field intensity attains a higher value in the region of the smallest diameter. Absorption, scattering, fluorescence, and resonance can occur in the waist region. Light resulting from fluorescence is collected along with the transmitted and scattered light in the divergent region.

The heat source for tapering may be a gas burner, a micro-heater with electrical resistance (Brambilla *et al.* 2009) or a CO_2 laser beam (Kakarantzas *et al.* 1999). The flame brushing technique provides optical fiber tapers with minimum optical losses and maximal robustness (Brambilla *et al.* 2009). It uses a gas burner as a heat source, and is probably the most used method for manufacturing tapers (Brambilla *et al.* 2010). In such a technique a small flame moving back and forth and embracing an optical fiber provides local heating, acting along a determined length of the fiber called the ‘hot zone’. A high-degree of accuracy in defining the taper shape can be obtained by controlling the fiber stretching rate and the flame movement (Brambilla, 1997). Typical values of these parameters are in the order of *mm/min* and *mm/s*, respectively, with the flame having a diameter of approximately 2,0 *mm* (Kenny *et al.* 1997). The efficiency of this technique depends on the stability and uniformity of the process, which can be affected by vibration during stretching, or flame temperature instability (Graf *et al.*).

A fiber taper rig is in development in the Laboratory of Instrumentation at Santa Catarina State University and details of its assembling and characteristics may be obtained in the reference (Graf *et al.*).

The optical signal attenuation at the fiber optic taper output and the produced taper profile are the quality control parameters (Graf *et al.*). A biconical taper with an excess loss less than 10% may be considered adiabatic according to the adiabaticity criteria for fiber optic tapers (Black *et al.* 1991). The original taper rig configuration was operating with a low cost commercial air aspirated gas heater (Jackwal HT6020), using a mixture of butane and propane as fuel in the proportion of 75% and 25% respectively. It presented reasonable results, being capable to produce fiber optic tapers in the micrometric range (minimum of 10 μm) (Graf *et al.*). However, it was difficult to be fully automated having serious limitations on flame control, flame stability, and keeping a continuous flow for longer periods of time. Therefore, an improved heat source for the taper rig was necessary to be implemented in order to solve these issues and reach smaller taper diameters. A heater operating with high- purity oxygen-butane gas mixture, with the gas flow controlled by digital mass flow controllers was the chosen system configuration.

Although the main parameters and the flame width were known (Kenny *et al.* 1997), there was no report about the flow rates or the gas heater tip diameter, and to the author's knowledge these data are still to be published. The goal of this work is to present the procedures used to evaluate the flow rates of oxygen and butane gases and report these values to completely describe the flame brushing characteristics in a fiber optic taper rig.

2. METHODOLOGY

To implement the flame-brush in the taper rig, a systematic study was necessary. The starting point was the determination of the flow rate produced by the commercial air aspirated gas heater previously used in the process, providing a reference magnitude of the flow rate. The experiment for such purpose was based in the mass conservation law. Initially the gas heater mass was measured and after a controlled period of time, corresponding to a taper production, its mass was measured again. By knowing the mass variation and the elapsed time, an average mass flow rate was obtained. Since the flow controllers operate at approximately the ambient pressure and temperature (1 *atm* and 25°*C*), these values were used to evaluate the gas mixture density in order to obtain the volumetric flow rates.

A flame is defined as a self-sustaining propagation of a localized combustion zone at subsonic velocities (Turns, 2000). Such zone is characterized by fast exothermic reactions often accompanied by emission of light. Flames may be described as stationary flames, being continuously fed by the fuel gas, or as freely propagating flames moving through an initially resting gas mixture. Stationary flames may be either premixed flames, where fuel and oxidant are mixed before approaching the combustion zone, or diffusion flames where the mixture of the reactants and the combustion occur at the flame interface (El-Mahallawy and El-Din Habik, 2002). The nature of the premixed flames may also be laminar or turbulent, referring to the characteristic of the gas flowing. The heating system developed is operating with a premixed laminar flame. This type of flame has characteristic adiabatic flame temperature and flame speed. Adiabatic flame temperature is defined as the temperature reached by the combustion products when the combustion is processed adiabatically (Turns, 2000). The flame speed is defined as the velocity of a plane flame front that moves perpendicularly to its surface through a quiescent unburned reacting medium. Such velocity is a characteristic property of the mixture and is independent of the flame geometry, gas heater dimensions or flow rate (El-Mahallawy and El-Din Habik, 2002). Once the flame travels at a characteristic velocity, it may become stationary by doing the reacting medium to move in opposite direction. The laminar flow passing through the gas heater has a parabolic profile in nature, with the flow velocity near the tube wall tending to zero due to viscous effects, being responsible together with the heat losses to the heater for the flame stabilization at the top and for the shape of the flame (Turns, 2000, Glassman and Yetter, 2008). The shape of a premixed laminar flame is conical, where the presence of an external cone is also a characteristic due to the secondary reaction caused when carbon monoxide and hydrogen from the inner flame reach the atmospheric air (Turns, 2000). Thus, inside a flow velocity range, the flame shall stabilize such that locally, in the inner cone surface, the flame speed is equal to the normal component of the flow velocity, as illustrated in Fig. (1).

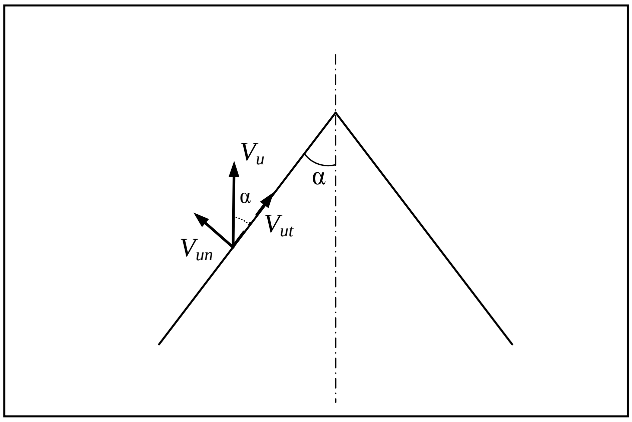

Figure 1. Conical profile representation of a stabilized flame.

Therefore,

$$V_f = V_u \cdot sen\alpha \tag{1}$$

where V_f is the flame speed and V_u the local flow velocity. If it is assumed that the conical angle α is constant, which is equivalent to assume a constant flow velocity profile, then by knowing the flow velocity V_u the volumetric flow rate of the reactants Q_r may be found by the following relation:

$$Q_r = \frac{V_f}{sen\alpha} \cdot \left(\frac{\pi \cdot d^2}{4} \right) \tag{2}$$

where d is the diameter of the gas heater port.

Once knowing the flow rate of the reactants, the flow rate of each mixture component may be found by stoichiometric analysis. The main parameter to be determined in the equation (2) is the flame speed. For such purpose the software Chemkin® was used. The models and idealizations adopted in this software may be obtained in the Chemkin Theory Manual (CHEMKIN-PRO, 2008). The interest in this approach is to obtain the characteristic flame speed of the gas mixture being analyzed, and its main influencing factors. The subsequent procedure was to evaluate the accuracy of this model, applying it to the commercial gas heater, in which experimental results were available. The cone geometry of the flame produced by the commercial gas heater was measured with the software DataThief, from which one could obtain the conical angle α, i.e., the angle between the flame sheet and the vertical plane. The continuity equation was used to find the mass flow rates, and together with the respective densities the volumetric flow rate of both fuel and air was obtained. By using thermodynamics relations the following equations for fuel and oxidizing agent volumetric flow rates are obtained:

$$Q_{fuel} \cdot \rho_{fuel} = y_{fuel} \cdot Q_r \cdot \rho_r \cdot \frac{M_{fuel}}{M_r} \tag{3}$$

$$Q_{oxi} \cdot \rho_{oxi} = Q_r \cdot \rho_r - Q_{fuel} \cdot \rho_{fuel} \tag{4}$$

where, Q_{fuel} is the volumetric flow rate of the fuel; Q_r is the volumetric flow rate of the total reactants; Q_{oxi} is the volumetric flow rate of the oxidant; y_{fuel} is the fuel mole fraction; M_{fuel} is the fuel molar mass; and M_r is the total reactants molar mass.

The stoichiometric equation for reactions of hydrocarbons with air is represented generically by:

$$C_xH_y + \left(x + \frac{y}{4} \right) O_2 + 3.76 \left(x + \frac{y}{4} \right) N_2 \rightarrow xCO_2 + \left(\frac{y}{2} \right) H_2O + 3.76 \left(x + \frac{y}{4} \right) N_2 \tag{5}$$

Thus, the combustion of one mole of propane/butane gas mixture, assuming that the atmospheric air consists of 21% O_2 and 79% N_2, is represented by the following reaction:

$$\left(0{,}25C_3H_8 + 0{,}75C_4H_{10} \right) + 6{,}125O_2 + 23{,}03N_2 \rightarrow 3{,}75CO_2 + 4{,}75H_2O + 23{,}03N_2 \tag{6}$$

The density of the total reactants mixture may be obtained by assuming this mixture as an ideal gas at ambient pressure and temperature (1 *atm* and 25°*C*).

This procedure was used afterwards to estimate the flow rates of the mixture of butane and oxygen. Although this approach presented a significant deviation, it showed the order of the variation to be expected, and as the digital mass flow controller permits to precisely adjust the flow rates, the exact supposed relation between oxygen and butane can be obtained, reducing consequently the uncertainties involved.

Numerical simulation was used to analyze how determined parameters such as equivalence ratio, nitrogen concentration, and inlet gas temperature influence in the characteristic flame speed. Equivalence ratio, ϕ, and nitrogen concentration, φ, are defined respectively as:

$$\phi = \frac{(\text{Fuel/Oxygen})_{\text{Real}}}{(\text{Fuel/Oxygen})_{\text{Stoichiometric}}} \tag{7}$$

$$\varphi = \frac{\text{O}_2}{(O_2 + N_2)} \tag{8}$$

A flame with flow rates obtained from theoretical analysis was produced and its conical angle α measured with the same procedure described previously. The angle measured was then used in the theoretical model allowing one to obtaining the theoretical to experimental deviation. With the calculated results, digital mass flow controllers were specified and incorporated in the fiber taper rig.

3. RESULTS AND DISCUSSION

The procedure used to evaluate the mass flow rate of the commercial gas heater was repeated five times and the results are presented in Tab. (1). The density of each component was evaluated with its respective partial pressure and temperature from The National Institute of Standards and Technology website, resulting ρ_p = 0,45239 kg/m^3 and ρ_b = *1,8225* kg/m^3 for propane and butane respectively.

Table 1. Mass and time variation and its respective values of mass and volumetric flow rates evaluated in each experiment for the commercial gas heater.

$\Delta m_{fuel,1}$ (g)	$\Delta m_{fuel,2}$ (g)	$\Delta m_{fuel,3}$ (g)	$\Delta m_{fuel,4}$ (g)	$\Delta m_{fuel,5}$ (g)	$\Delta \overline{m}_{fuel}$ (g)
1,514	1,912	1,676	1,565	1,484	1,630
Δt_1	Δt_2	Δt_3	Δt_4	Δt_5	$\Delta \bar{t}$
30”06,3’	30”12,7’	30”01,2’	29”51,2’	30”00,1’	30”02,3’
$\dot{m}_{fuel,1}$ (g/h)	$\dot{m}_{fuel,2}$ (g/h)	$\dot{m}_{fuel,3}$ (g/h)	$\dot{m}_{fuel,4}$ (g/h)	$\dot{m}_{fuel,5}$ (g/h)	$\overline{\dot{m}}_{fuel}$ (g/h)
3,017	3,797	3,350	3,145	2,968	3,255
$Q_{fuel,1}$ (l/min)	$Q_{fuel,2}$ (l/ min)	$Q_{fuel,3}$ (l/ min)	$Q_{fuel,4}$ (l/ min)	$Q_{fuel,5}$ (l/ min)	$\overline{Q}_{fuel}$ (l/ min)
0,0221	0,0278	0,0245	0,0230	0,0217	0,0238

An averaged value of Q_{fuel} = 0,238 *l/min* was obtained for the volumetric flow of the fuel gas mixture. Although this simple experiment gave an idea of the fuel flow magnitude, it did not provide the necessary accuracy to properly specify the operation range of the digital flow controllers, since they operate with a different gas mixture and thus different flame properties. To obtain the main characteristics of the butane-oxygen combustion, an analysis resorting to numerical simulations was necessary. The resulting flame speed for the propane (25%) and butane (75%) fuel mixture, for stoichiometric combustion with air (21% O_2 and 79% N_2) at ambient conditions (1 *atm* and 25°*C*) was 45,44 *cm/s*. A value of 44,8 *cm/s* for n-butane at 1 *atm*, 25 °*C*, in stoichiometric combustion is reported in the reference (Glassman and Yetter, 2008). A picture of the flame produced by the commercial gas heater, and another with the considered geometric model, are depicted in Fig. (2) below:

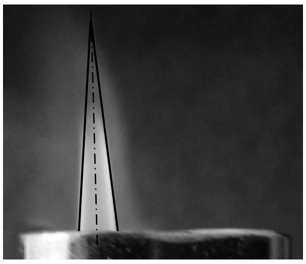

Figure 2. Flame produced by the commercial gas heater.

The flame cone geometry depicted in Fig. (2) was measured with the software DataThief, presenting the basis to the height ratio of a/h = 0,174, where a is the basis of the triangle in the model and h its height. Thus the angle between the flame sheet and the vertical plane is α = 5,0º. The port diameter of the commercial gas heater is d = 2,0 *mm*. Substituting these values in equation (2), we obtain Q_r = 0,983 *l/min*. The mole fraction and molar mass of the fuel mixture are y_{fuel} = 0,0332 and M_{fuel} = 54,61 *kg/kmol*, respectively. It is also found for the molar mass and density of the total reactants the values M_r = 29,71 *kg/kmol* and ρ_r = 1,214 kg/m^3, respectively. Finally, from equation (3) the volumetric flow rate of the fuel mixture is found to be Q_{fuel} = 0,0320 *l/min*. This value is about 30% higher than the experimental. This deviation is a consequence of the uncertainties and simplifications adopted. If the flame produced by the gas heater is not stoichiometric, but it is a flame having oxygen in excess, then the flame speed and the fuel mole fraction tend to decrease, reducing the value of the fuel volumetric flow rate, as can be seen from equation (2). In the numerical simulations the combustion of butane-oxygen and butane-air mixtures were studied. Results of such analysis are depicted in Fig. (3), (4) and (5). In these charts T and p represent the gas inlet condition.

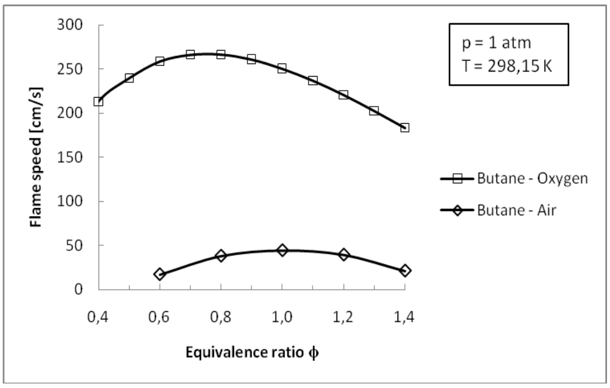

Figure 3. Equivalence ratio effect on the flame speed for butane-oxygen and butane-air combustion.

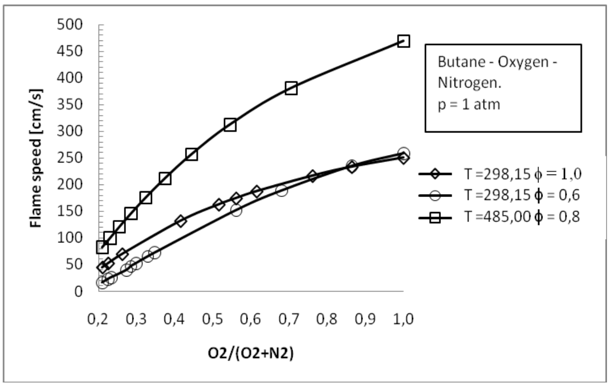

Figure 4. Nitrogen effect on the flame speed. The initial point corresponds to combustion with air whereas the last point to combustion with oxygen.

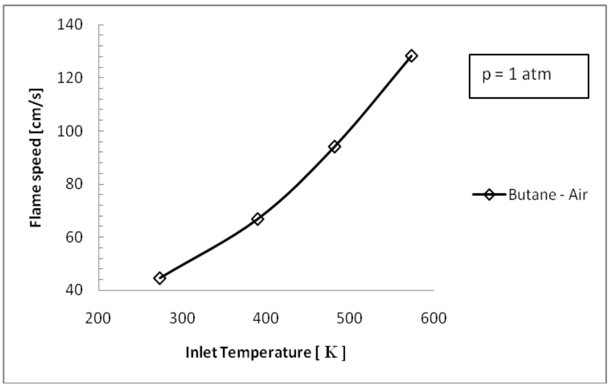

Figure 5. Inlet temperature effect on the flame speed for butane-air combustion.

From the graphs above, it is observed that the flame speed is much larger for the combustion of butane-oxygen. The inlet temperature and the nitrogen concentration have a significant effect on the flame speed and it continuously increases with these parameters. The effect of the equivalence ratio is to increase the flame speed up to a certain point, passing through a maximum and starting to decrease after this point. The adiabatic flame temperature as function of these same parameters is presented in Fig. (6), (7) and (8).

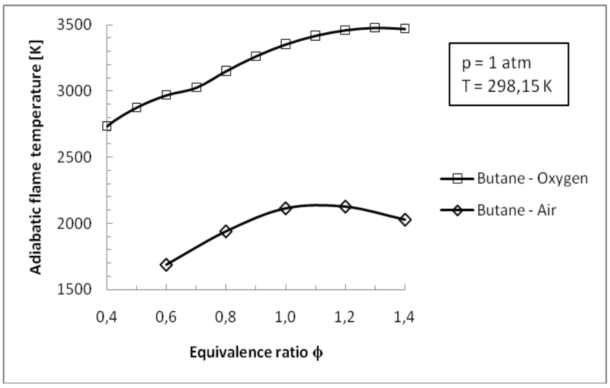

Figure 6. Equivalence ratio effect on the adiabatic flame temperature of butane-oxygen and butane-air combustion.

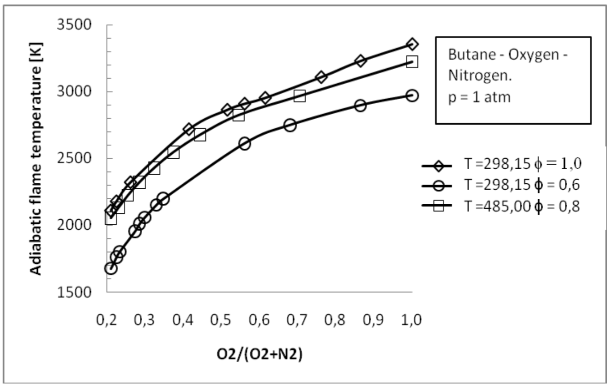

Figure 7. Nitrogen concentration effect on the adiabatic flame temperature. The initial point corresponds to combustion with air whereas the last point to combustion with oxygen.

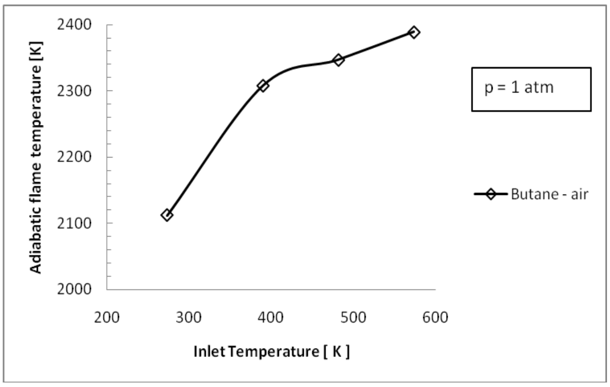

Figure 8. Inlet temperature effect on the adiabatic flame temperature of butane-air combustion.

It can be seen that the adiabatic flame temperature is much larger for combustion with butane-oxygen than with butane-air. Although these values do not reflect the actual values due to heat losses, it is useful for a qualitative analysis of the flame temperature behavior. From Fig . (7), we note that the inlet gas temperature has a smaller influence over the adiabatic flame temperature than the equivalence ratio. To estimate the flow rates in the butane-oxygen combustion, it is assumed that a stoichiometric combustion in ambient conditions (1 *atm* and 25°*C*) occurs. From Fig. (3) it is found that the flame speed at these conditions is V_f = 250,4 *cm/s*. It is also assumed a value of α = 10° for the angle between the sheet flame and the vertical plane. The gas heater developed has a port diameter of d = 0,87 *mm*. Thus, from equation (2) Q_m = 0,514 *l/min, w*here Q_m is the volumetric flow rate of the butane-oxygen mixture. The stoichiometric relation for this mixture combustion is given by equation (5) without nitrogen. Thus:

$$C_4H_{10} + 6{,}5O_2 \rightarrow 4CO_2 + 5H_2O \tag{9}$$

The mole fractions of butane and oxygen are obtained from the previous equation. With such mole fractions and their respective molar masses one finds M_m = 35,47 *kg/kmol* and ρ_m =1,450 kg/m^3 for the mixture molar mass and density, respectively. Finally, from equation (3) one obtain Q_b= 0,066 *l/min.* To evaluate the oxygen volumetric flow rate, it is used the equation (4) for ambient conditions (1 *atm* and 25°*C*), which provides Q_o = 0,446 *l/min.* It is also known that one of the main issues in the fiber optic taper manufacture is the fracture caused in the fiber due to the gas flowing around it. Therefore the flow rates must be as low as possible to properly manufacture fiber optic tapers. Thus, the angle α in the equation (7) is expected to be larger than 10º. This fact gave the authors enough confidence to expect the actual values to be lower than the obtained. The flame produced by the theoretical values of the flow rates obtained Q_b = 0,066 *l/min* and Q_o = 0,446 *l/min* is shown in Fig. (9). The ratio of the cone basis to the cone height obtained was a/h = 0,410, giving a value of the conical angle equal to α = 11,6º. Thus, the values of butane and oxygen flow rates theoretically calculated, corresponding to this angle, become respectively Q_b = 0,057 *l/min* and Q_o = 0,385 *l/min*, which reveals a deviation of 13,6 % from the experimental values.

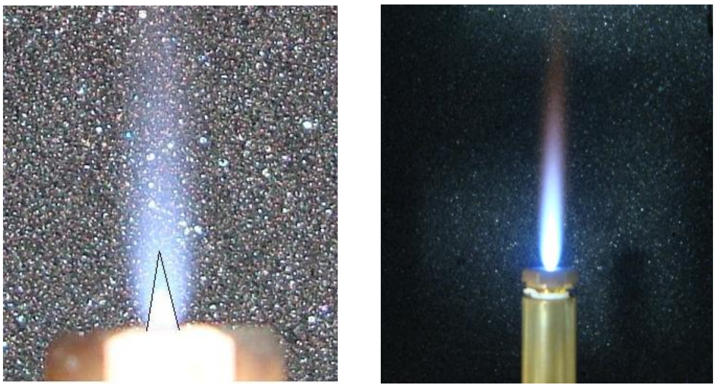

Figure 9. Flame produced with butane and oxygen flow rates Q_b = 0,066 *l/min* and Q_o = 0,446 *l/min* respectively.

3.1. TAPER MANUFACTURE

As it was expected, the calculated flow rates were too large, fracturing the fiber in the manufacturing process; however, it provided a nominal flow rate for the specification of the mass flow controllers, even considering such values as overestimations. Thus, it was significantly reduced, being necessary to empirically determine the flow rates necessary to manufacture fiber optic tapers. A correct flame configuration was found to be Q_b = 9,00 *ml/min* and Q_o = 21,00 *ml/min*, which was capable to easily produce fiber optic tapers of 2,0 μm. The pictures presented in Fig. (10) and

(11) below show respectively the flame attained with the described flow rates and a fiber optic taper of 1,5 μm manufactured using such flame. The program was set to manufacture a taper with diameter of 5,0 μm, but the result was taper with a smaller diameter as depicted in Fig. (11). The measured temperature of the flame in the manufacturing point was 950*ºC*. Figure (12) presents the normalized optical power passing through the fiber during the manufacturing process. The total loss during the process was 4,52%, agreeing with the adiabaticity criteria for fiber optic tapers (Black *et al.* 1991). It shows that the optical taper rig is properly manufacturing fiber optic taper with diameter less than 2 μm, reaching nanometric diameters around 1 μm with relative ease. Since an optical microscope was used, the micrometric resolution allowed the photograph of only these diameters.

Figure 10. Flame produced with butane and oxygen flow rates Q_b = 9,00 *ml/min* and Q_o = 21,00 *ml/min* respectively.

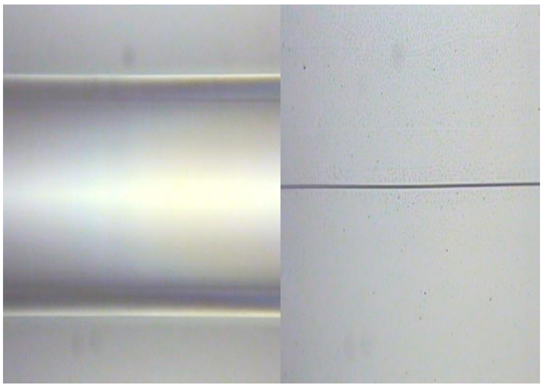

Figure 11. A silica optical fiber with diameter of 125 μm, and a fiber optic taper with diameter of 1,5 μm. Both images are amplified 20X.

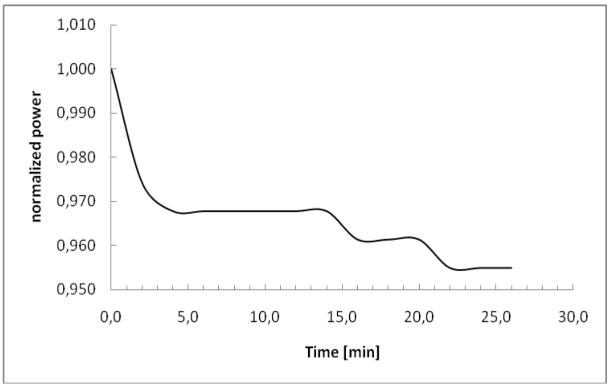

Figure 12. Optical loss through the fiber optic taper during the manufacturing process corresponding to the taper depicted in Fig. (11).

4. CONCLUSION

This paper described a technique to estimate low flow rates of gases in a micro gas heater used in a fiber optic taper rig. Since such a flame-brush was not completely characterized in the context of fiber optic taper rigs literature, the authors provided this complete characterization of the mass and volumetric flows in this device. To illustrate the applicability of the system, micro-metric fiber optic tapers were manufactured reaching the nano-metric threshold around 1 μm. As a future development, the authors intend to characterize the fiber taper manufacturing process while producing tapers with nano-metric diameters, in a well controlled environment, as a function of mass flow in the gas heater.

5. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

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