APPLICATION OF AN EFFERVESCENT ATOMIZER IN THE COMBUSTION OF USED RECYCLED OIL

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ABSTRACT

This paper reports the application of an effervescent atomizer to the combustion of used recycled oils. This research is a follow up of a research done previously, ending up with a comprehensive characterization of the atomization of used oils with an effervescent atomizer, which included point measurements of drop sizes and velocities of the produced sprays.

A test facility was designed and constructed, which included: a furnace with up to 300 kW thermal input and a swirl generator as a part of the burner set for the application of the effervescent atomizer. Other auxiliary facilities were also included, such as: cooling system, air supplies and pre-heating gas burner.

Combustion tests were performed with used recycled oil having a viscosity of 46 mm^2/s (50ºC) and a heating value of 44.4 MJ/kg. Results included qualitative observations of the ignition and flame stabilization, and LDA velocity measurements of the flow produced by the swirl generator with and without flame.

Preliminary tests may anticipate a good performance of the swirl generator in the process of fuel/air mixing inside the furnace. However, future work is needed to evaluate the level of emissions. Flame configuration was found to be highly dependent on spray characteristics.

1. INTRODUCTION

The disposal of used oils is currently a problem of major concern. One of the main reasons refers to the volume of used oil, which in Portugal amounts to 35 000 tones per year of collected oil. Amongst the technical solutions available, the energy recovery through combustion or re-refining back to a virgin base oil are those preferable. Although there is considerable debate on the merits and drawbacks of either solution, the combustion solution is still one with great potential. The reasons are two fold: a) it represents the use of an energy resource with a high heating value, thus reducing the demand on the conventional fuels; b) the economic benefits relatively to the re-refining solution.

One of the main axes of the directive 75/439/EC on used oils, amended in 1987, is that, among the different options for recovery, priority is given to the regeneration over their incineration. However, several studies clearly demonstrate that, Member States of the EU do not favour regeneration of used oil but, on the contrary, are widely using used oil as fuel in industrial applications [1].

Out of the 1 730 kt of used oil accounted per year in the EU, roughly 50% is used as an energy source in the EU [1]. Among this option, cement kilns play an important role: in Europe 35% of the energetically used oil is burnt in cement kilns. Other options are based upon the use of conventional liquid fuel boilers. However, this solution has various problems of concern, which result from the fuel characteristics: high viscosity, carbon deposits, and particulate. These characteristics yield a problematic atomization (previous heating) and subsequent deficient combustion resulting in soot and gaseous emissions.

It is well understood that pollutant formation can be mitigated through correct combustion, which in turn depends upon the atomization of the liquid. Of particular interest is the NO_x formation, which is closely related with the droplet size. One of the main mechanisms of NO_x formation depends on the temperature and residence time of the combustion mixture, which should be the lowest (thermal NO_x). This requirement can be met by producing a nearly homogeneous fuel-air mixture and burning far from stoichiometric conditions (lean or rich).

Previous studies have provided a very comprehensive characterisation of an effervescent atomizer [2,3]. Because of the internal dynamics of the nozzle, the results have shown that a very fine spray can be produced even at very low operating pressures and with no previous heating required. The outer orifice is fairly large and the nozzle obstruction is likely to be reduced. These characteristics make the effervescent atomizer very promising for used oil combustion.

Effervescent atomization is a method of twin-fluid atomization that involves bubbling a small amount of gas into the liquid stream before it is ejected from the discharge orifice of the atomizer. This technique was first developed by Lefebvre and his co-workers in the late 1980s. During the past decade, many detailed experimental studies have been carried out to determine the performance and spray characteristics of effervescent atomizers over a wide range of operating conditions. Sovani et al [4] presented a very comprehensive review of the effervescent atomization. This paper summarizes the results obtained from investigations of effervescent atomizer performance (variations in atomizer design, liquid properties and operating conditions), reviews current theories on the basic mechanisms involved in the atomization process, provides an overview of current applications and suggests possible areas for future applications. Of particular interest is the application in combustion systems, especially with low value and less refined fuels containing high levels of impurities and a wide range of physical properties. Features like lower injection pressures, smaller drop sizes, smaller gas flow rates and larger orifice diameters make this type of atomizer very promising for the applications with such fuels. Another advantage of the effervescent atomizer-produced sprays is the presence of air (atomizing gas) in the spray core, which increases the air/fuel mixing process, yielding a reduction in the pollutant emissions.

Practical applications of the effervescent atomizer in combustion systems include: gas turbine combustors, furnaces and boilers, IC engines and incinerators [4].

Sankar et al [5] developed a swirl effervescent atomizer for application to industrial and residential boilers; the combustion studies only included qualitative measurements: the flame produced by kerosene combustion was completely blue. This suggested an absence of soot, indicating complete combustion of the fuel that resulted from finer atomization of the liquid fuel.

Loebker and Empie [6] designed an effervescent atomizer for spraying a pulping industry by-product, called black liquor (a viscous liquid of widely varying composition with up to 80% solid suspension), into a heat recovery boiler. The performance of this atomizer was compared with a conventional spray system Vee-Jet™ nozzle, used with the black liquor. They found that while the near nozzle structure of the Vee-Jet nozzle showed a mesh of interwoven, unbroken strands of liquid, effervescent atomizer showed much smaller liquid fragments and drops. In addition, the effervescent atomizer produced drop sizes typical of current recovery boilers (2-3 mm) over a range of liquid viscosity.

The application of effervescent atomizers in waste incineration represents another field of great interest due to: the reduced sensitivity to liquid viscosity, small dependence to the size of the discharge orifice – reducing clogging – and lower liquid flow velocities in the discharge orifice, greatly reducing erosion problems.

The main objective of this study was to evaluate the application of an effervescent atomizer to the combustion of used recycled oils, following previous work on the characterization of such sprays [2,3]. The objectives of the project can be stated as follows:

1. Design and construction of a furnace and heat exchanger in order to perform combustion tests up to 300 kW;
2. Design and construction of the burner for the application of the effervescent atomizer, which include: swirl generator and secondary air supply system;
3. To study the ignition conditions, flame stability, flame length and flame temperature;
4. To study the flow inside the furnace in order to optimize the combustion;
5. To study the emissions and their relationship with the combustion conditions

Goals 1 to 4 were already achieved and are partially presented in this paper. Goal 5 is now being prepared and will be developed in the near future.

2. TEST FACILITIES

2.1 Effervescent Atomizer

The effervescent atomizer used in this study was based on the design presented in Ferreira et al [3]. In order to enable its assembly in the burner set some modifications have been introduced. Fig. 1 shows the detailed design of the plain-orifice effervescent atomizer. A modular design was adopted in order to enable the interchanging of some components of the atomizer. However, only a combination of components was used in this study. The aerator consisted of a brass tube with 6.4 mm inside diameter and 82.9 mm long, perforated with 96 holes with 0.75 mm diameter, arranged in a 8x12 staggered layout. The discharge orifice consisted of a plain-outlet orifice with a convergence from 6.4 mm down to a straight final orifice of 1.2 mm in diameter and of 3 mm in length. The oil and air flows were injected through the top of the atomizer, as showed in Fig. 1, to enable the assembling into the burner. The atomizer's body had two straight holes with 10 mm diameter to receive the two ignition electrodes.

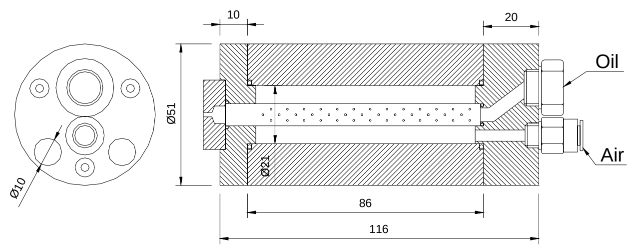

Fig. 1: Detailed design of the plain-orifice effervescent atomizer

2.2 Test Rig

Fig. 2 shows schematically the main components of the test rig: furnace (1), oil burner (2), auxiliary gas burner (3) and propane gas supply (4), oil supply system (5), atomizing (or primary) air supply (6), secondary air supply (7), cooling system (8) and flue gases exhaust (9).

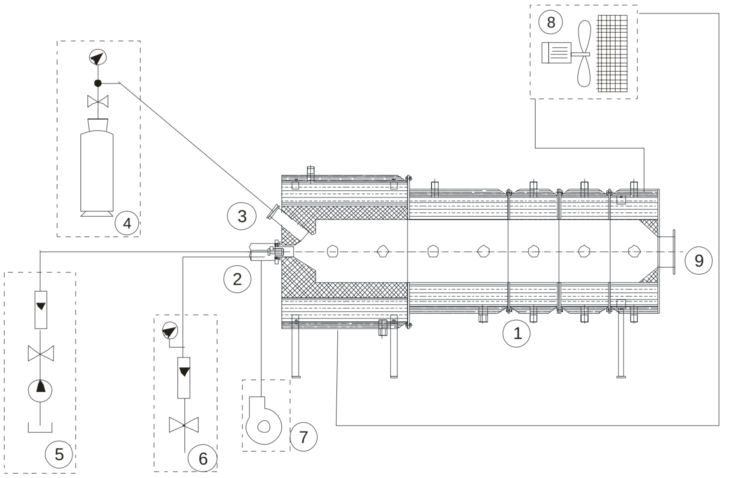

Fig. 2: Layout of the test rig

The furnace had a combustion chamber, cylindrical in shape, with an inside diameter of 0.5 m and 2.7 m long. Its axis was horizontal due to height restrictions of the laboratory. The furnace comprised five water-colled steel segments: one with 1 m long, one with 0.8 m and three with 0.4 m. The first segment (1 m long) was lined with a 0.115 m thick layer of refractory. All of them had a water jacket for refrigeration with 0.18 m thick. The outer surfaces were insulated with a ceramic fiber 0.05 m thick. Along the furnace the segments had seven pairs of diametrically opposed windows with 0.110 m diameter and 0.4 m apart from each other, in order to provide optical access to the flame. Some steel pipes with ½" nominal diameter were also passed trough the furnace wall to enable other measurements such as furnace static pressure and flame temperature. A set of 21 thermocouples were installed at several points inside the furnace walls to record wall temperatures. Flue gases exit the furnace through a stack with 0.25 m internal diameter and 10 m high, made of stainless steel, insulated with mineral fiber.

The oil burner included the effervescent atomizer and a rotary vane tangential swirl generator. The swirl intensity was regulated by adjusting the angle of the rotary vanes. The burner gun had an internal diameter of 0.051 m. The secondary air was injected tangentially between another tube (burner tube) and the burner gun. This burner was controlled by an oil control Danfoss BHO 64 connected to ignition electrodes, flame photo-detector, secondary-air pressostat and oil electro-valve.

The furnace also incorporated a single-port atmospheric-type gas burner for refractory preheating prior to oil firing. This burner was controlled by a specific gas burner control Pactrol CSA6, performing ignition, flame detection and gas shutt off. After being turned off this burner was carefully blocked to avoid unwanted air entering the furnace.

The oil supply system, already described in Ferreira et al [3], comprised a spur gear pump connected to an oil container (1 m^3), an helical screw flow meter and pressure gauge. The atomizing air was supplied by the compressed air mains after passing through a filter. A rotameter with a pressure gauge and a needle valve enabled the control and measurement of pressure and air flow-rate. Both flow meters were individually calibrated.

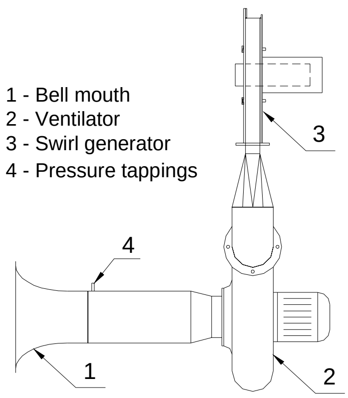

Fig. 3: Secondary-air supply system with bell shaped entrance

Secondary air was supplied by a centrifugal fan into the swirl generator. Flow-rate was measured at the entrance of the fan with a bell shaped inlet section, as represented in Fig. 3. The flow-rate was determined by measuring the static pressure at the throat of the bell shaped entrance, which was calibrated by calculating the discharge coefficient C_D. This coefficient was determined by measuring the velocity profile of a transparent pipe upstream of the ventilator exit, using 2D measuring LDA system. An average C_D of 0.96 was obtained, demonstrating the good design of the bell shaped entrance.

Used recycled oil supplied by AUTO VILA, reference OQ1 was used through the experiments. The most important properties were determined: density – 898 kg/m^3; kinematic viscosity – 46 mm^2/s; higher heating value – 44.4 MJ/kg.

2.3 LDA Configuration

A two color (2D) Dantec LDA system has been used to measure point velocities of the flame and secondary air. An Argon-Ion laser (water cooled) with 6W was splitted into two color beams (blue and green, 488 nm and 514.5 nm wave length, respectively). The beams were steered into the transmitting/receiving optics (Dantec 55x modular LDA optics– based 85 mm FiberFlow system) through a fiber cable. A lens focal length of 600 mm enabled point measurements along half diameter of the furnace. Because velocity masurements to determine the swirl intensity of the swirl generator have been done outside the furnace, a lens with 310 mm focal length was used. The scattered light was collected in the backscatter mode. Flow sensitivity was provided through a 40 MHz Bragg Cell. The transmitting/receiving optics were mounted on a 3D programmable traversing table (Lightweight traverse table). In this way, it was possible to control the measurement position from a computer, using a standard IEEE-488 interface. The Doppler signals were processed through a couple of spectrum analysers (Dantec BSA's 57N20/57N35 models). The burst detection criteria, processing parameters of the processor and traverse movement coordinates were set from the computer, which was also used to store and analyse the results. BSA's operation was in Burst processing mode. All the hardware control, setup, configuration, data acquisition and statistical processing of data was controlled by an integrated software package, Dantec BSA Flow v. 1.4.1.

3. RESULTS AND DISCUSSION

Two categories of results are presented here: qualitative and quantitative. The qualitative results are related with the first tests and commissioning of the furnace. Quantitative results include LDA measurements of velocity profiles to determine the performance of the swirl generator.

Qualitative results:

Before starting the oil combustion the furnace was first started with the auxiliary gas burner, in order to pre-heat the refractory which took about one hour. The water jacket was previously filled with water and the cooling system was operational. After this period the oil burner was initiated and ignition was accomplished immediately. The flame was stabilized after a short period, by adjusting oil and secondary air supplies, until we reached a small particulate emission through the stack. The furnace run at a nominal power input of 150 kW during several hours and all the equipment, including the cooling system, seemed to be appropriate and working normally.

Quantitative results:

The results presented here include: velocity measurements of the secondary air injection though the swirl generator to the burner, taken outside the furnace, and velocity measurements of the flame inside the furnace.

The first tests were undertaken outside the furnace with single secondary air injection. Silicon oil was used as the seeding media, introduced in the flow with a nebulizer at the bell mouth entrance. The tests were done in front of an extraction hood to avoid respiration of the silicon/air mixture. The atomizer was located inside the burner gun with the nozzle exit 30 mm inside from the burner tube end.

Fig. 4 shows a complete plot of axial and tangential velocity profiles at three different configurations of burner tube diameter and swirl vanes angle. Two plots were taken with burner tube diameter of 85 mm, the first with rotary vanes full opened (swirl #1) and the second at middle closed position (swirl #2). A third plot was done with a burner tube diameter of 67 mm and the vanes full opened (swirl #1).

The measurements were taken for three lines at different axial distances from the burner exit (25, 75 and 125 mm); each line begins at the centre of the cone to the outside, at 2 mm intervals.

In order to compare the performance of each configuration, the swirl number (or intensity) was determined at each individual axial position. The secondary air swirl number, S_s, was defined by Beér and Chigier [7] by integration of axial and tangential velocity profiles as follows:

$$S_S = \frac{G_w}{G_x\, d_0} \tag{1}$$

where G_w is the axial flux of tangential momentum, G_x is the axial flux of axial momentum, without the pressure term, and d_0 is burner diameter. The momentum fluxes can be written as:

$$G_w = \int_0^{r_1} 2\pi\rho w u r^2 dr \tag{2}$$

$$G_x = \int_0^{r_1} 2\pi\rho u^2 r\, dr \tag{3}$$

where r_1 represents the external radius of the velocity profile, u and w are axial and tangential velocities.

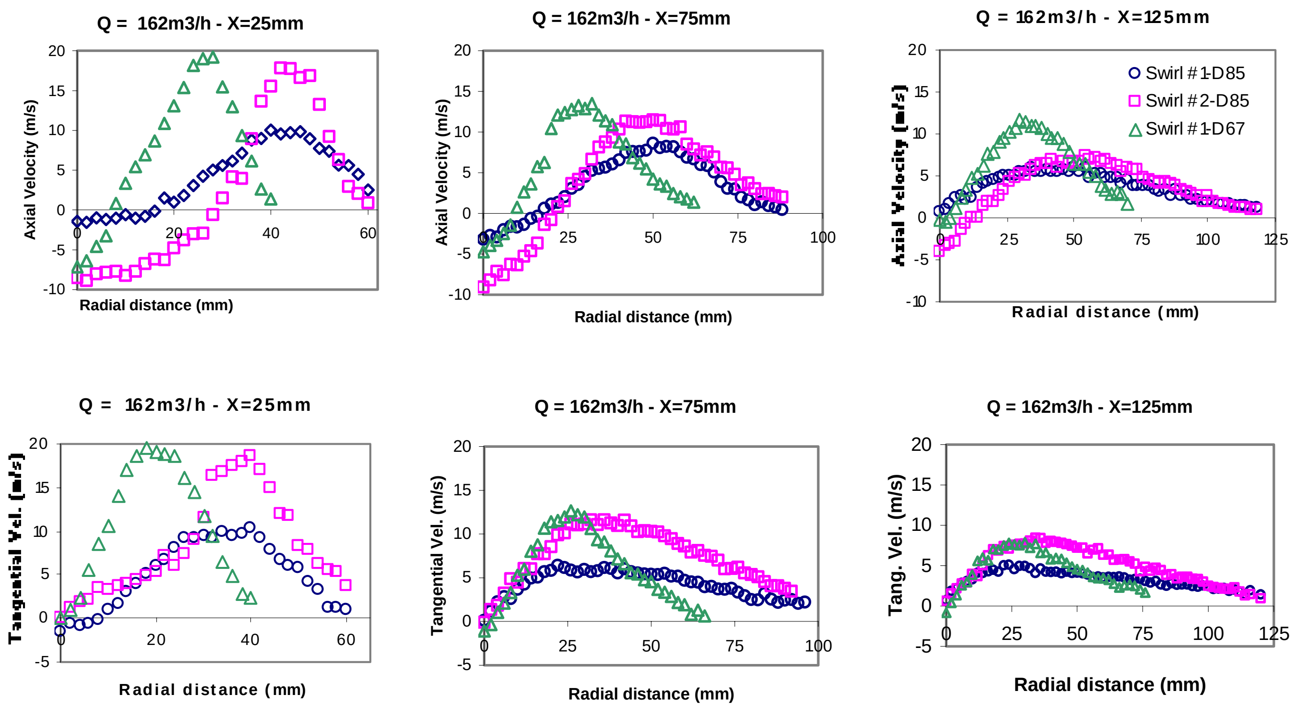

Fig. 4: Axial and tangential velocity profiles produced by swirl generator at three different configurations.

Table 1 presents the swirl number for each line at which measurements were taken for the results presented in Fig. 4.

Table 1: Swirl number at different distances from the burner exit at Q = 162 m^3/h

X	Swirl number		
	D = 85 mm		D = 67 mm
	Swirl #1	Swirl #2	Swirl #1
X = 25 mm	0.9	1.5	0.2
X = 75 mm	1.6	1.7	0.9
X = 125 mm	1.8	2.0	1.1

As expected the swirl number increases with increasing distance from the burner exit, due to smaller axial velocities away from the exit. Closing the rotary swirl vanes (Swirl #2 – D85 mm) results in higher swirl numbers, for the same tube diameter. However, this effect is decreasing as we move from the exit. Changing the tube diameter to a smaller one (D = 67 mm) results in much lower swirl numbers. The only beneficial effect of decreasing the tube diameter is to shorten the cone angle and increase the penetration of the secondary air profile, which could have some advantages depending on the size and configuration of the fuel spray. The higher negative axial velocities were obtained with tube diameter 85 mm and swirl #2 along the three lines measured, representing the highest recirculation of the secondary air. This is an important feature in order to have the necessary fuel/air mixing in the near burner zone. Other measurements have been done at different air flow rates and the results showed to be similar.

In order to evaluate the flow inside the combustion chamber, axial and tangential velocity profiles of the flame were measured through one of the glass windows of the furnace. A cyclone type seeding generator was used to inject aluminium oxide particles inside the flow, some point downstream of the swirl generator. A supply of compressed air at very low pressure (around 50 kPa) was enough to inject the necessary particles inside the secondary air flow.

Figure 5 presents the axial and tangential velocity profiles of the flame at the same oil and secondary air flow rates and two different atomizing air flow rates, giving different atomizing Air to Liquid Ratio (ALR) in mass of 0.20 and 0.16. Velocities were measured in the first window of the furnace, at 285 mm from the burner exit, from the centre to the outside of the flame, at 5 mm intervals.

Both profiles present a centre core of positive axial velocities and an outer region of recirculation. Tangential velocity profiles show similar order of magnitude and direction. However, while the flame at ALR=0.20 extends trough a large portion of the furnace, the flame at a lower ALR is confined at a very short region. This gives evidence of how atomizer performance can have paramount influence in the flame configuration and hence in the combustion conditions of liquid fuels. A spray with smaller and uniform drop size distribution gives rise to smaller flames with higher rates of air/fuel mixing (this should be the case of ALR = 0.20). The axial profile at ALR = 0.16 could be a result of long burning times necessary to burn larger drops in the central core of the spray.

Several parameters may influence the flame characteristics and hence the combustion performance: oil and secondary air flow rates, ALR, swirl intensity, dimensional characteristics of the burner, and relative position of atomizer and burner tube. Further work is needed to evaluate the individual influence of such parameters.

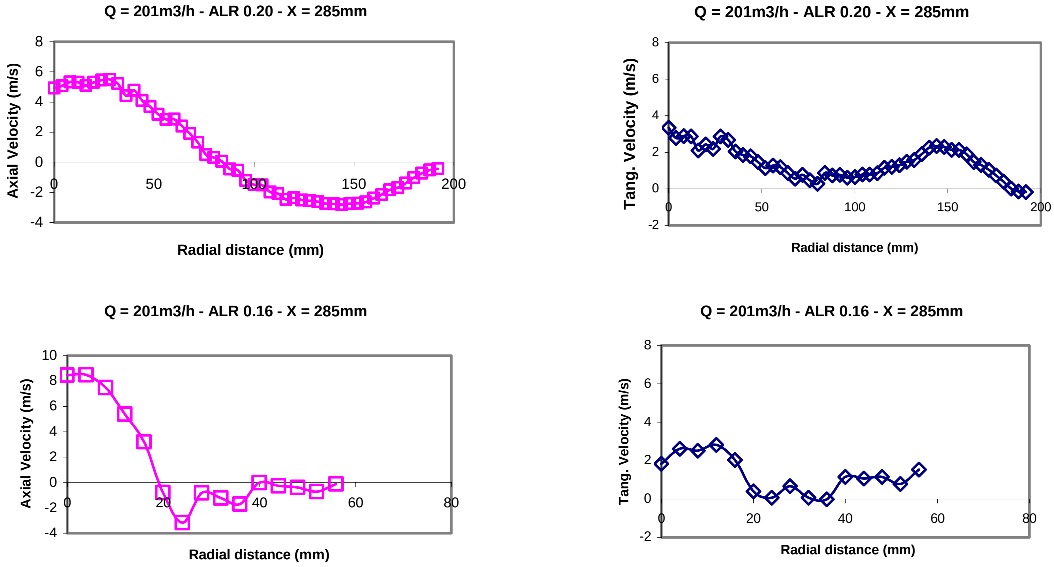

Fig. 5: Axial and tangential velocity profiles of the flame at 285 mm from the burner exit: secondary air flow rate – 201 m^3/h; ALR = 0.20 and 0.16

4. CONCLUSIONS

A combustion facility was successfully design and constructed for testing the performance of liquid spray combustion systems, including a burner set with swirl generator for the application of an effervescent atomizer to the combustion of used recycled oil. Preliminary tests may anticipate a good performance of the swirl generator in the process of fuel/air mixing inside the furnace. LDA measurements of secondary air velocities provided some understanding of the influence of burner tube dimensions and swirl intensity in the flow configuration. Evidence has been given of the paramount influence of liquid spray characteristics in the flame configuration. Future work including flue gases emission is expected to bring further evidence on the performance of the effervescent atomizer in the combustion of used recycled oil.

NOMENCLATURE

C_D	Discharge coefficient (dimensionless)	Q	Flow rate (m^3/s)	w	Tangential Velocity (m/s)
d_0, D	Burner diameter (m)	r	External radius (m)	X	Axial distance (m)
G_x	Axial momentum (kg m/s^2)	S_s	Swirl number (dimensionless)	ρ	Density (kg/m^3)
G_w	Tang. momentum (kg m^2/s^2)	u	Axial velocity (m/s)	ALR	Air to Liquid Ratio in mass (dimensionless)

AKNOWLEDGMENTS

The authors express their gratitude to the Portuguese Science Council (FCT) for their grant (POCTI/EME/42121/2001). In addition, the contribution of the furnace manufacturer MORISA and the used oil supplier AUTO VILA SA (company dedicated to the recovery and treatment of used oils) is acknowledge.

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