Discharge coefficient and operational flow characteristics of multihole effervescent atomizer

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Abstract
The study of effervescent atomizers is being conducted with the aim to develop an effervescent atomizer for industrial burners that will generate a fine and stable spray in a large turn-down ratio, and provide a symmetrical flux distribution. The atomizer is powered with light heating oil and uses air as an atomizing medium. The atomizer is expected to replace Y-jet atomizer frequently used in burners. This research is a follow up of a research done previously with a single-hole effervescent atomizers with various geometrical features of both, the aerator and the body of the atomizer. Based on results of this study, a multi-hole effervescent atomizer was designed in several geometrical modifications. Except size spectrum and flux distribution of the spray, other flow characteristics of the atomizers are very important from the point of the operation of the atomizers. Among them, flow rates of both mediums as function of pressure of both and GLR (Gas-to-Liquid Ratio) are most important from the point to adjust the system for predetermined turn-down ratio. Other important parameter is discharge coefficient. Three basic variants of multihole effervescent atomizers have been studied that differ in the geometry. One of the basic requirements in designing the nozzles was to prevent neighboring sprays generated by individual holes from possible merging. This could lead to coalescence of droplets due to low droplets velocities in the outer spray region and consecutively to an increase of SMD. It could also prevent combustion air from better mixing with fuel. Attention was also given to an easy control of atomizer operation in a real application in burners, i.e. to ensure a possibility to operate the atomizer with a well determined pressure difference between fuel and air. Paper suggests some recommendations for designers of effervescent atomizers.

1. Introduction

Effervescent atomizers are becoming more and more commonplace in numerous engineering applications in which a liquid must be fragmented into droplets. Effervescent atomizers in combustion applications lead to lower pollutant emissions due to presence of air in the spray core. As high grade hydrocarbon fuels become scarce, the effervescent atomizers will have to be replaced with other designs that can handle less refined fuels. Major advantage of effervescent atomizers is their relative insensitivity to fuel physical properties and ability to perform over a wide range of liquid flow rates and can provide good atomization over a wide range of operating conditions. Furthermore the E-atomizers can have larger orifice than conventional atomizers which alleviates clogging problems and facilitates atomizer fabrication.

When designing effervescent atomizers for industrial furnaces, a main attention must be paid to their real operation. Control system of both lines – liquid and gas – must be able to satisfactorily perform over required liquid flow rates. As the effervescent atomizers are operated at relatively low GLR, the pressure difference between liquid and air can be relatively low but this latter may significantly change with changing liquid flow rate and with different internal geometry of the atomizer. To obtain a stable operation and control of the atomizer we need that the pressure difference is approximately by one order lower than the absolute value of pressure of both fluids. The main reason is certainly the dynamic range of regulators that keep constant pressure of liquid at the pump discharge, tolerance range of steam or air pressure used as an atomizing fluid, shocks in the pipelines as a result of shutting and opening valves (for example when starting operation of additional burners), characteristics and accuracy of the regulator, and characteristics of different control devices like flaps, valves etc.

In the design of effervescent atomizer, it is often necessary to determine the exit area required to achieve a certain liquid flow rate for given values of air pressure and GLR. Thus, knowledge of the discharge coefficient plays an important role in the design process. It is also desirable to know the discharge coefficient of a given nozzle in order to predict the liquid flow rate under certain operating conditions. Unfortunately, it is difficult to determine a priori the relationship between liquid flow rate and nozzle exit area, since atomizing air and liquid both flow through the same discharge orifice.

Several geometrical configurations of multihole effervescent atomizers have been studied with the aim to establish relationship between flow rates of both fluids at different pressures of both and at different GLR and discharge coefficients as function of air pressure and GLR.

2. Experimental facility and atomizers

Figure 1 shows a schematic layout of the experimental facility. It consists of a gear pump #14 that supplies light heating oil from a main fuel tank 16 through a set of filters, control valves and flowmeters into the atomizer #7. The compressed air is delivered either from the central plant or from a two stage compressor #1 depending on the required pressure through an air chamber #2 and set of filters and control valve into the atomizer. Spray is collected in a vessel #12 and returned to the main supply tank. The collector is connected to an oil mist separator that keeps the spray zone free of aerosol but doesn't distort the spray. The gear pump delivers the oil with a pressure up to 3MPa, pressure of the compressed air can reach 2MPa. The maximum flow rate of the oil can reach 1800 kg/hour. Pressures and temperatures readings are taken at the atomizer inlets for both the fuel and air. The pressure measurements are complemented by the pressure difference measurement. The fuel is injected vertically downwards into the ambient atmosphere. The sampling distance was set to 152mm from the atomizer orifice.

In the test rig, the atomizer is turned by an appropriate angle from vertical so the spray is directed perpendicularly downward. To enable measurements of only one individual spray, a special collector was made and fixed to the tip of the atomizer. The collector is made in such a manner that doesn’t influence pressure field in the atomizer and returns all untested sprays to the main supply tank. The collector doesn’t disturb the observation field for additional PLIF and PDA measurements.

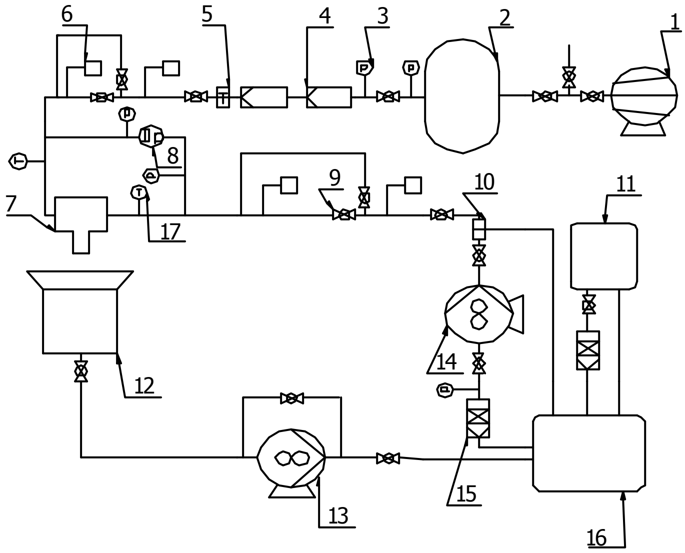

Fig. 1 Schematic layout of the experimental facility

In total four geometrical variants of atomizers have been studied, that are labeled E6, E7, E8 and E9 – see Fig.2. Atomizers were designed according methods published in [1, 2 and 3]. In all atomizers the fuel flows in the central part, the air flows from an annular space that is around the central part. E6 has the aerator with the inner diameter of 14mm. There are in total 72 holes of the diameter of 1.2mm arranged in 9 rows, in each 8 holes turned through 45°. The last row is 74mm from the nozzle orifice. E7 atomizer has the same body of the aerator, in which is placed a special shaft that forms an annular gap through which the fuel flows. The shaft has the conical-cylindrical shape so the annular gap gradually enlarges from 1mm to 4mm. After the last row of the aerator holes, the shaft has the cylindrical shape. The tip of the E6 and E7 atomizers has a conical shape with 6 holes of the diameter of 1.2mm. The axis of the holes form a full angle of 60°. E8 and E9 atomizers have a conical shaft inside the aerator so the gap gradually enlarges from 1mm at the position of the first row of aerator holes. There are 168 holes of the diameter of 1.2mm in 21 rows, 8 holes in one row always turned through 45°. The last row of holes ends up at the position of the tip of the conical shaft. The tip of nozzle has 6 holes of the diameter of 2.2mm. With E8 atomizer, the axis of the holes form a full angle of 60°, in E9 atomizer the full cone is 90°.

As a fluid, light heating oil was used with the flow rate in the range from approximately 0.05l/s to 0.5l/min, the GLR was adjusted between 1 and 10%, the pressure of the fuel was set in the range from 0.2, to 1.0 MPa. In the test rig, the atomizer is turned by an appropriate angle from vertical so the spray is directed perpendicularly downward. To enable measurements of only one individual spray, a special collector was fabricated and fixed to the tip of the atomizer. The collector is made in the way not to influence pressure field in the atomizer and returns all other individual sprays to the main supply tank. The collector doesn't disturb the observation field for additional PLIF and PDA measurements.

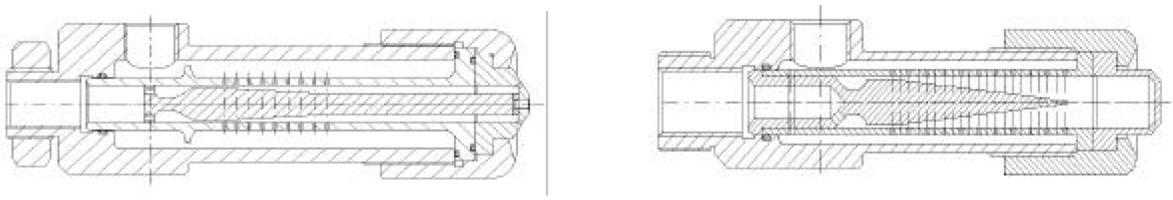

Fig.2 Schematic layout of atomizers E6 (without shaft), E7 – left and E8 (E9) - right

3. Experimental procedure a results

Investigations have been conducted with the aim to provide most useful information for designers of atomizers and burners. The main attention was given to operational conditions of the atomizers. For E atomizer it is crucial to reliably control an optimal value of GLR for different burner loads. Also, stability of the spray is a big concern. In all measurements, stability evaluated visually was analyzed and taken into consideration.

First measurements have been done with atomizers E6 and E7 in the range of fuel pressure difference 0.1 to 1 MPa and GLR from 1% to 5% and with turn-down ratio 1:5. From visual observations and video sequences, the spray was stable and homogenous in the turn-down ratio 1:5 for indicated GLR. Only at GLR 1% the turn-down ratio that ensures yet stable spray was only 1:4. Both atomizers E6 and E7 demonstrate the following features:

- at constant atomizing air pressure, GLR increases with decreasing pressure difference $p=p_{fuel}-p_{air}$
- the higher is the fuel pressure, the higher is the pressure difference $p=p_{fuel}-p_{air}$ we need to keep a constant GLR. This is namely remarkable with E7 atomizer likely due to the shaft inside the aerator – see Fig.3.

The principal difference between E6 and E7 atomizers lies in the absolute values and in the sign of the pressure difference $p=p_{fuel}-p_{air}$. With E6, p ranges from –40mbar for lowest fuel pressures and highest GLR to +20mbar for highest fuel pressures and lowest GLR. With E7 the pressure difference moves from +2mbar to approximately +600mbar, i.e the pressure difference is always positive and is changing in a much larger interval. This can be seen from Fig.3.

To stably operate and control atomizers, we need that the pressure difference p is approximately by one order lower than the absolute value of both fluids. The reason is mentioned in 1. Introduction and it is mainly the dynamic range and sensitivity of regulators. From it results that with E6 we need to increase operational pressure of air what could be done for instance by reducing number of aerator holes which on the other hand could lead to changes in the two- phase regime.

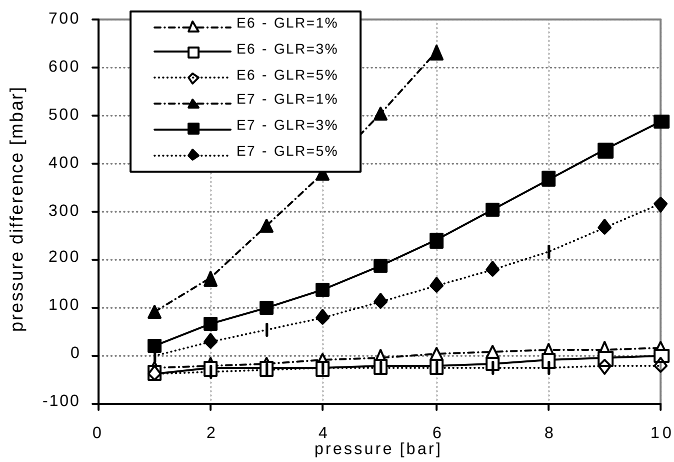

Fig.3 Pressure difference $p=p_{fuel}-p_{air}$ for GLR 1; 3; 5%

Let’s assume that E6 will be adapted in the way that the absolute value of p will be about the same as for E7. Then, in the whole turn-down ratio, E6 will have higher pressure of air than of the fuel, i.e. $p=p_{fuel}-p_{air}$ will be negative, whereas p in E7 will be positive.

There are several options how to control the atomizers that effect the choice of atomizer:

1. constant air pressure while controlling fuel flow rate. This option has disadvantage in the large amount of air at low burner power. Both, E6 and E7 can be used.
2. constant pressure difference $p=p_{fuel}-p_{air}$. This option is not suitable with E7 since with reducing power and thus the fuel flow rate, also GLR will be decreasing which will certainly lead to low quality of spray and perhaps instabilities can occur.
3. control of both fluids with a predefined operational regime. Both atomizers E6 and E7 can be operated in this way.

Considering that E6 is simpler and easier to fabricate, E6 was chosen for additional tests. The tests consists in reducing number of holes in the aerator to obtain pressure difference $p=p_{fuel}-p_{air}$ by one order lower that the absolute fuel pressure, i.e. p should be approximately 0.1MPa. Progressively 3, 6, 7 and 8 rows of aerator holes were made inactive by pasting a plastic foil over, starting from the nozzle tip. Finally, 8 upstream rows of holes were pasted over. The experiments were conducted only for GLR 3%. Results can be seen in Fig.4. Pressure difference substantially increases only with 8 rows blocked, either down- or upstream ones. But neither in this case the pressure difference is sufficiently large to fulfill requirements of the control system. At lower values of air pressure the spray demonstrates instabilities that intensify with number of blocked rows. Instabilities are reduced when upstream instead of downstream rows are blocked.

Based on the E6 and E7 tests and results, new atomizers labeled as E8 and E9 were designed and tested. Their geometry is described in 2. Experimental facility and atomizers. The main goal was to obtain a higher pressure difference between fuel and air and remove instabilities at lower pressures. The first goal was achieved by placing a diaphragm in the air line prior to the atomizer. The second goal by making larger number of holes in mixing chamber through which air is injected into fuel.

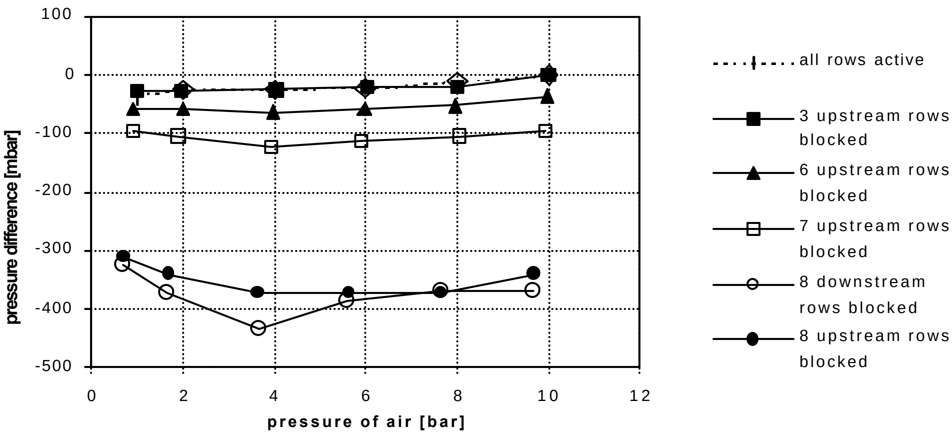

Fig.4 Atomizer E6: p as function of air pressure and number of blocked rows of holes

The following operational scenario was adopted:

Case 1. Standard operation of the atomizer E8 that consists in the set up of a given pressure of air at p_{air}= 0.2, 0.6 and 1MPa and then the adjustment of the required GLR at 3, 5 and 10%. As a result, an appropriate fuel flow rate was obtained. From the point of operation of burners unacceptable scenario.

Case 2. The same as ad1), an orifice with cross section of 21.2mm^2 placed in the atomizer inlet air pipe to increase pressure difference p_{air}-p_{fuel}. GLR was adjusted to obtain the same fuel flow rates as in Case 1.

Case 3. Same as ad2), but constant pressure of air as a leading parameter adjusted to 0.1MPa and GLR adjusted to obtain the same fuel flow rates.

Case 4. Constant pressure difference p_{air}-p_{fuel}=100 mbar as leading parameter, fuel flow rate set to same values as in Case 1.

Case 5. Same as Case 3, smaller orifice with cross section of 1.8mm^2 placed in the atomizer inlet air pipe.

Several conclusions can be drawn from the investigation.

In all measurements, the flow rate of fuel was in the range approximately 0.050 to 0.400 l/s. In Case 3, the fuel pressure needed to obtain the required range of flow rates was between 0.98 to 1.08MPa and GLR was changing from 82 to 3%. In Case 4, both fuel and air pressures had to be adjusted to keep the pressure difference constant with changing the fuel flow rate. Fuel pressure was changing from 0.069 to 1.01MPa, the air pressure from 0.075 to 1.02MPa. GLR was changing from 1.7 to 4.4%. In Case 5, the fuel pressure needed to obtain the required flow rates was between 0.084 and 0.52MPa, GLR was changing from 9 to 2%. From these figures we can conclude that operation of the E atomizer is strongly dependent on the pressure operational conditions, namely how the atomizer is controlled. Pressure difference and GLR as function of fuel mass flow rate can be seen in Fig.5 and 6. As can be seen the pressure difference p_{air}-p_{fuel} moves in the range from negative to positive values. Positive values are reached when an additional orifice is placed in the inlet air pipe prior to the atomizer (Case 2, 5 and partly 3). The orifice increases the air pressure and thus the pressure difference which in Case 5 increased dramatically (note that the values of *dp* are multiplied by 0.1 to fit the coordinate scale). As the fuel flow rate increases, the positive pressure difference decreases which also means that the volumetric air flow rate decreases (mass air flow rate keeps constant as the air pressure is adjusted at constant value).

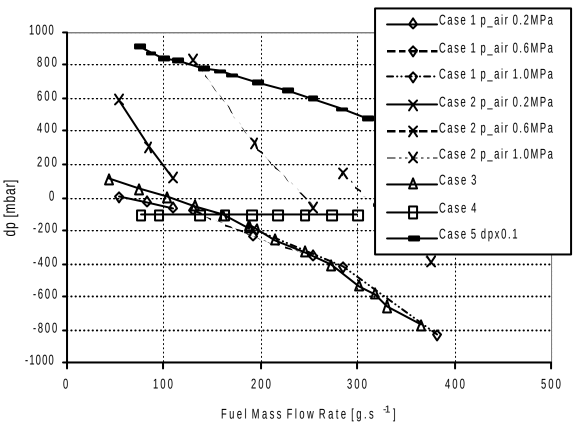

Fig.5 Pressure difference p_{air}-p_{fuel} as function of fuel mass flow rate

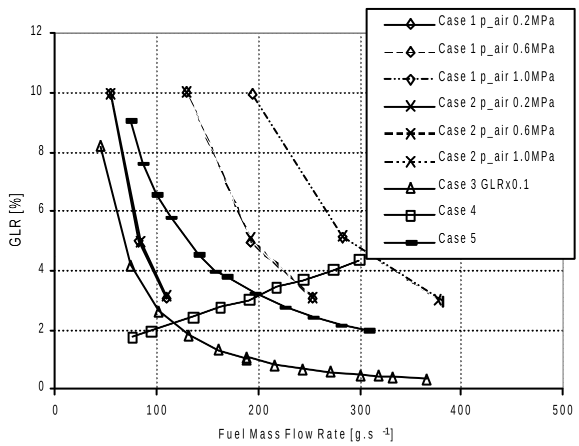

Fig.6 GLR as function of fuel mass flow rate

In case 3 (also with an orifice) the pressure difference changes from positive to negatives as the fuel flow rate increases. To increase fuel flow rate we need higher pressure of fuel to overcome the constant air pressure of 10 bar. In this case GLR for low fuel flow rates is extremely high (see Fig.6 and note that GLR is multiplied by 0.1).

4. Discharge coefficient

Values of discharge coefficient, C_d, were calculated for all the data acquired for atomizer E8 (case 1 to 5) and E6 (with blocked rows of holes). C_d is defined as

$$C_d = \frac{\dot{m}_{fuel}}{A\sqrt{2\, p_{fuel}\ \rho_{fuel}}}$$

where $\dot{m}_{fuel}$ is the liquid mass flow rate, p_{fuel} is the fuel pressure, ρ_{fuel} is the liquid density, A is the cross-sectional area of the discharge orifice. Individual discharge coefficients for the above-mentioned variants can be seen from fig.7 as function of the fuel volumetric flow rate. This graph gives more evidence about the atomizer operation in a burner at different operation conditions and scenario. It can be seen that the discharge coefficient is relatively low and increases with fuel flow rate. But if the pressure difference across the atomizer is kept constant (here at 100mbar), the discharge coefficient also is constant even the GLR is changing. This is due to the changing atomizing air pressure. For the same fuel flow rate, the highest values of C_d were obtained for constant air pressure of 1MPa with an additional orifice of small cross section 1.8mm^2 placed in the air inlet pipe prior to the atomizer (scenario No.5). Effect of GLR on C_d can be seen in Fig.8. We can see that C_d is decreasing with GLR increasing. Also the effect of atomizing air pressure is clearly seen – C_d decreases with pressure decreasing. These findings are consistent with [1].

These characteristics together with knowledge of discharge coefficients are predominant in a practical design of E atomizers for industrial burners and their control systems, respectively.

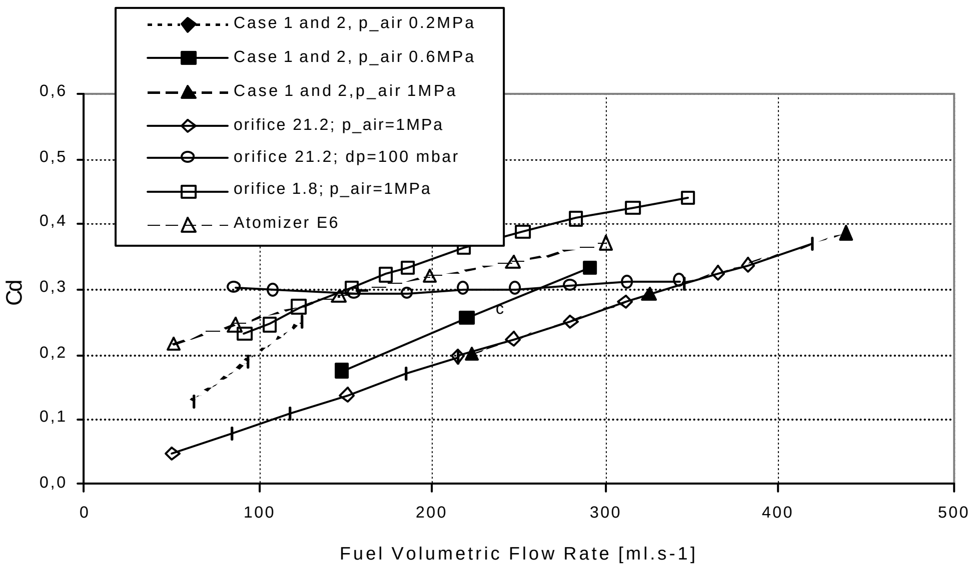

Fig.7 Discharge coefficient as function of fuel flow rate

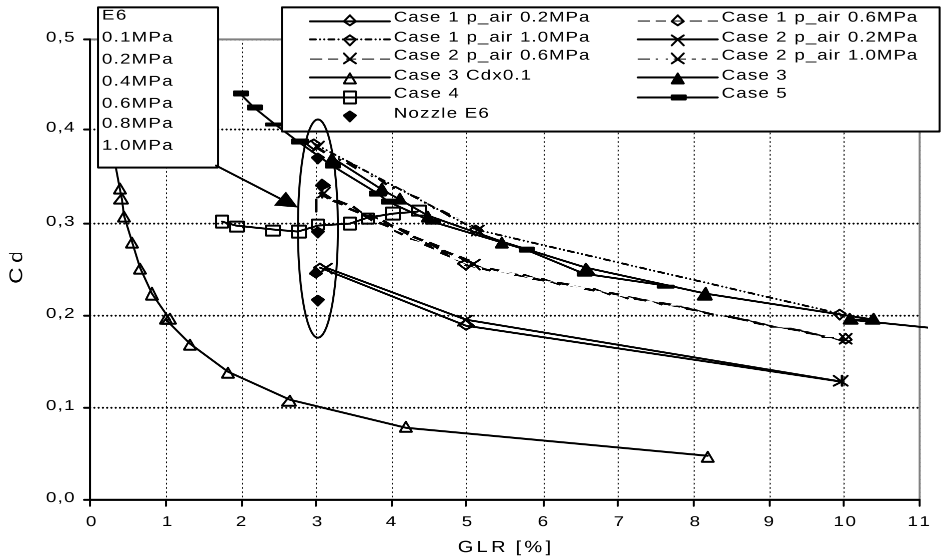

Fig.8 Discharge coefficient as function of GLR

5. Conclusions

Several variants of effervescent atomizers were tested with the aim to design an atomizer that could be easily operated in industrial burners. Different characteristics were investigated that could help in designing process. Attention was given mainly to parameters that are predominant in design and operation of atomizer control system. That is the way how to operate the atomizer – whether with constant air pressure, constant pressure difference and/or other way. It shows that the optimal way that would ensure keeping GLR at an optimal value would be to control both fluids –fuel and air independently. There was also a question raised about the absolute values of pressures of both fluids in relation to pressure difference between air and fuel. To reliably control the atomizer we need that the pressure difference is about one order lower than the absolute pressure of air. This can be achieved by placing an orifice in the air inlet pipe prior to the atomizer.

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References

[1] Chen S K and Lefebvre A H 1994 Discharge coefficients for plain-orifice effervescent atomizers, *Atomization and Sprays*, **4**, 275-290

[2] Chin J S and Lefebvre A H 1995 A Design procedure for effervescent atomizers, *J. of Eng. For Gas Turbines and Power,* **117** 266-271

[3] Koren M, Katoshevski D, Sher E and Kholmer V 2000 Energy Consideration and experimental study of effervescent atomizers *Proceedings of Ilass-Europe 2000 II.7*