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A DESIGN PROCEDURE FOR "LIQUID TO AIR" TYPE ATOMISERS BASED ON AIR AND WATER MIXTURE OUTFLOW VELOCITY

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The paper proposes a procedure which enables to determine selected geometric and operating parameters for twin-fluid liquid-to-air atomisers with internal mixing. The presented approach assumes that in order to ensure proper operation of an atomiser it is necessary to design its structure and flow parameters in such a way so that the flow inside the mixing chamber has a dispersive character. In order to calculate a required exhaust cross-section for the analysed atomiser, conditions within the exhaust plane: pressure, density and outflow velocity were estimated. In order to determine diameter and number of orifices supplying the liquid to the mixing chamber of the investigated atomiser type, a multi-parameter analysis based on numerical fluid mechanics was performed. The final part of the paper presents selected results obtained from experimental stand measurements made on an atomiser designed according to the presented procedure.

Keywords: liquid atomisation, liquid to air atomisers, design procedure

1. INTRODUCTION

Popular use of liquid-to-air atomisers is not accompanied by adequate development of computational techniques. When attempting to design such an atomiser, one encounters a number of difficulties attributable to the character of a two-phase flow system. Because of that, in most cases calculations are based on empirical formulas or directly on test results (Orzechowski and Prywer 2008). Experimental testing becomes an essential part of the process leading towards a final solution within the engineering process. Calculations are used in the first stage of such a process, but their reults may not be considered as final information on the design and parameters of the investigated solutions. This paper proposes a design procedure for twin-fluid internal mixing atomisers, where the gaseous phase is dominating (liquid-to-air atomisers). General information about liquid-to-air atomisers can be found in (Ashgritz, 2011; Chin and Lefebvre, 1995; Orzechowski and Prywer, 1994). Regardless of design details, each atomiser of this type comprises of (Jedelsky et al., 2007):

- components restricting liquid and gas flows before the contact zone (pipelines, chambers etc.);
- mixing chamber – a volume where contact between gas and liquid occurs;
- nozzle – transporting created gas-liquid mixture outside the device;
- duct between the mixing chamber and the nozzle.

Liquid-to-air atomisers are used in many branches of industry, e.g. in flue gas denitrification technology for power boilers (Krawczyk and Badyda 2014). Among other parameters that dictate the spray qualities of a twin-fluid atomiser are geometry (Liu et al., 2006), operating parameters, and liquid properties (Broniarz-Press et al., 2009; Ramesh et al., 1985).

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The presented approach is aimed at finding certain geometric parameters (diameters of the mixing chamber, duct leading to the nozzle and nozzle, as well as number and diameter of orifices supplying liquid to the gas flow) and operating parameters (supply pressure of liquid and air, air flow) for the assumed flow of dispersed liquid.

2. DESIGN PROCEDURE

In the presented approach it is assumed that in order to ensure proper operation of an atomiser it is necessary to design its structure and flow parameters in such a way so that the flow inside the mixing chamber has a dispersive character. Results of two-phase flow structures in the pipes were presented among others by Koch and Noworyta (1992) or Troniewski (1989).

2.1. Determining diameter of the mixing chamber

In the first step the discussion aims at determining diameter of the mixing chamber of the designed atomiser, which would ensure a desirable flow character within possibly a wide range of the operating parameters. To fulfil that condition, the values describing character of the air-water mixture flow, i.e. G_g/λ and $\lambda\psi(Q_L/Q_A)$ must remain within specific limits defined for example by Chin and Lefebvre (1995). For a specified flow of the liquid this requires choosing appropriate diameter of the mixing chamber, proper pressure inside that chamber, and proper air flow. The two latter parameters may vary, but only in such a way that the two-phase flow is maintained within a specified regime. Individual parameters which define the character of the two-phase flow may be expressed by the following equations (Chin and Lefebvre, 1995).

- air mass flow G_p:

$$G_p = \frac{\dot{m}_p}{\pi \frac{D_c^2}{4}} \tag{1}$$

- coefficient λ:

$$\lambda = \sqrt{\frac{\rho_g}{\rho_{g\_st}} \cdot \frac{\rho_L}{\rho_w}} \tag{2}$$

- coefficient ψ:

$$\psi = \frac{\sigma_w}{\sigma_L} \cdot \left(\frac{\mu_L}{\mu_w}\right)^{1/3} \cdot \left(\frac{\rho_w}{\rho_L}\right)^{2/3} \tag{3}$$

- volumetric liquid flow Q_L:

$$Q_L = \frac{m_L}{\rho_L} \tag{4}$$

- volumetric air flow Q_A:

$$Q_A = \frac{m_A}{\rho_A} \tag{5}$$

Assuming that the liquid in question is water, and the gas is air, the coefficient ψ takes a value of 1. For the parameters mentioned above, i.e. water flow, air flow, chamber pressure and chamber temperature, it is possible to additionally determine characteristic parameters of the two-phase flow in pipes, such as:

- volumetric air fraction in the air-water mixture α;

$$\alpha = \frac{Q_A}{Q_A + Q_L} \tag{6}$$

- air to liquid ratio – *ALR*

$$ALR = \frac{m_A}{m_L} \tag{7}$$

2.2. Determining diameter of the exhaust nozzle

In order to determine the required outflow cross-section for the analysed atomiser, conditions within that cross section: pressure, density and outflow velocity need to be calculated. Pressure in the exhaust plane of the nozzle is a function of pressure in the mixing chamber and volumetric fraction of air. If the ratio of pressures in the chamber and in the space to which the mixture is released (ambience) is lower than a critical value, then the pressure at the exhaust plane is equal to the ambient pressure. For higher values of the pressure ratio, the pressure in the exhaust plane is equal to the critical pressure and the mixture velocity is equal to the speed of sound in that mixture. Critical pressure ratio for a two-phase flow (air, water) is a function of air volumetric fraction in the mixture. For $\alpha = 1$ it is the same as for the air, i.e. 0.528. For $\alpha < 1$ its value reduces. As studies show (Brennen, 2005), in the investigated range of α above 0.95, variability of the pressure ratio in question is small. Critical pressure for the air-water mixture in the exhaust plane may be calculated using Eq. (8) (Crowe, 2005):

$$\frac{p^*}{p_c} = \left[\left(\frac{k+1}{2} \right)^{\frac{4k}{3(k-1)}} + \left(\frac{k(1-\alpha_c)}{2\alpha_c} \right)^{\frac{4k}{3(k-1)}} \right]^{-3/4} \tag{8}$$

Knowing the exhaust pressure it is then possible to determine gas density at the same plane. Speed of sound in the exhaust plane may be calculated using the following formula (Brennen, 2005):

$$\frac{1}{c^{*2}} = \frac{\alpha^*}{kp^*} \left[\rho_L \left(1-\alpha^*\right) + \rho_G^* \alpha^* \right] \tag{9}$$

The parameter α^* in the presented calculation procedure has been determined from the published literature data (Brennen, 2005), which link its value to the value of the parameter α_c. According to the research results (Brennen, 2005) for $\alpha^* > 0.4$ it is justified to assume a linear relation between both discussed air fraction values.

$$\alpha^* = 0.7\alpha_c + 0.3 \tag{10}$$

Speed of sound in the air-water mixture strongly depends on the volumetric air fraction in the mixture. For $\alpha = 1$ it is the same as for the air. For $\alpha < 1$ its value reduces considerably. When $\alpha = 0$, it sharply grows to the value of speed of sound in water (Brennen, 2005).

For the ratios of mixing chamber pressure to the ambient pressure higher than the critical value, the mixture velocity in the exhaust is equal to the speed of sound within the mixture ($M = 1$).

Knowing density of gas in the exhaust plane and its velocity it is possible to determine the volumetric flow across that plane as a sum of the liquid flow Q_L and the air flow Q_A. Assuming that both components of the two-phase mixture pass across the exhaust plane with identical velocities, it is possible to calculate required cross-section of this exhaust.

$$A^* = \frac{Q_L + Q_A}{V^*} \tag{11}$$

An orifice with an area of A^* enables the required amount of liquid and air to flow for a given mixing chamber pressure.

2.3. Determining cross-sectional area of orifices supplying liquid to the mixing chamber

Because no principles for choosing area, diameter or number of orifices supplying liquid into the mixing chamber of the investigated atomiser type had been found in the literature, the authors employed ANSYS Fluent computational fluid dynamics tool to determine these values. The analysis was based on the Discrete Phase Model used to track droplet trajectories. A mixing chamber fragment with a length of ten diameters, i.e. 0.1 m, where the water was injected to the main air flow through 1 orifice was a subject of the numerical analysis. Water injection point was located 0.02 m from the domain inlet (Fig. 1).

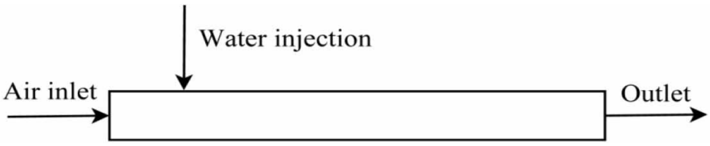

Fig. 1. Geometry of the computational area

Calculations were time-independent and turbulence was modelled using a RANS model. Uniform velocity distribution was assumed at the inlet cross section. Uniform static pressure was assumed at the outlet. The model took into account the effects of the water stream breakup (primary breakup), water droplet breakup (secondary breakup), and possible droplet collisions. It did not take into account effects of contact between droplets and walls; in particular film creation was ignored. The used models and settings are listed in Table 1.

Table 1. Main models and settings used for Ansys Fluent modelling

Solver type	pressure-based, steady
Energy equation	on
Turbulence model	realisable k-ε, enhanced wall treatment
Discrete phase	discrete phase model with unsteady particle tracking
Injection type	plain orifice-atomiser
Breakup model	stochastic secondary droplet model – SSD
Air density	ideal gas model

The analysis did not extend to the narrowing exhaust section of the nozzle. Because the analysed case was simplified – i.e. with fixed diameter of mixing chambers with only one liquid inlet – the results should be interpreted in the context of design assumptions of a specific atomiser, such as:

- diameter of the mixing chamber,
- length of the mixing chamber,
- relative position of water inlets into the mixing chamber.

The aim of the presented numerical analysis was a selection of optimal operating parameters of the mixing chamber, such as:

- liquid injection velocity;
- diameter of the injection orifices;
- liquid injection angle.

The design was considered acceptable if it ensured that droplets would not strike into the chamber walls and liquid streams would not collide each other. Penetration of the droplet trajectories in the direction perpendicular to the pipe axis was analysed.

Modelled geometry is shown in Fig. 1. Uniform velocity across the inlet was set at the inlet (Velocity Inlet type condition), with velocity value from 10 to 30 m/s, depending on the investigated case. Other inlet parameters were: total temperature 300 K, turbulence intensity 5% and hydraulic diameter 0.01 m. As for the exhaust, fixed static pressure equal to reference pressure was assumed. Reference pressure was set at either 3 or 6 bar, depending on analysed case. As already mentioned, water injection was implemented using DPM model and Plain Orifice Atomiser sub-model. Parameters assigned to each injection point included water mass flow, orifice diameter, injection direction and temperature (300 K).

The calculation geometry was discretised with 359,195 hexahedral finite volumes of high quality. Prior to starting an analysis it was ensured that the solution would be independent of the assumed discretisation. To ascertain that, some calculations had been made using a denser grid of 1,257,295 finite volumes. Observed results (jet penetration, average droplet diameter) obtained with both models were found to be identical, therefore the variant with lower computational cost was selected for further analysis.

Calculations were performed for all possible combinations of:

- air velocities – 10 m/s, 20 m/s and 30 m/s;
- water velocities – 1 m/s, 2 m/s and 3 m/s;
- angle between injection direction and chamber axis of 30°; 60°; 90°;
- mixing chamber pressure of 3 bar, 6 bar.

The obtained results from modelling clearly indicate that:

- increasing water injection angle increases droplet penetration depth;
- increasing water injection velocity increases droplet penetration depth;
- diameter of formed droplets is directly proportional to the water inlet orifice – average diameter of droplets in the mixing chamber is similar to that of the orifice;
- increasing pressure in the mixing chamber reduces droplet penetration depth.

Of course, the depth of penetration observed in the modelling results depends on the distance from injection location and grows along with this distance.

The chart below (Fig. 2) presents an exemplary relation between the depth of penetration 30 mm from the injection point, and ratio of water velocity at injection orifice to the air velocity in central pipe before the mixing chamber.

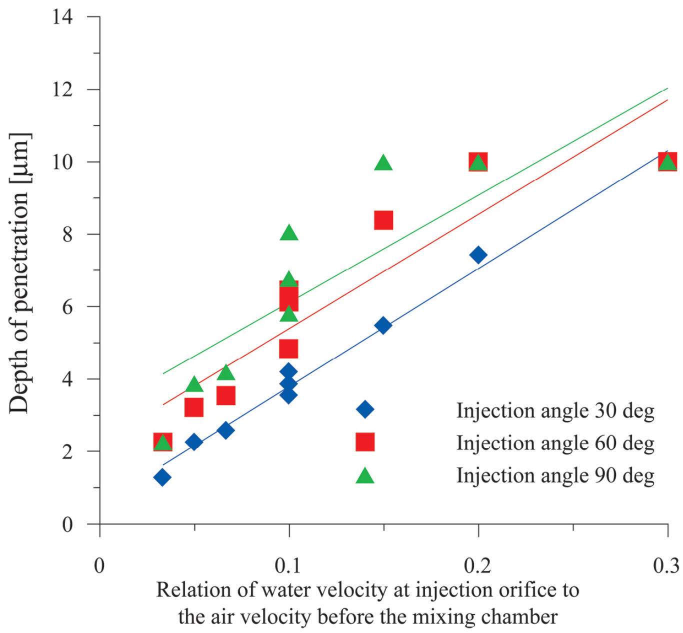

Fig. 2. Depth of penetration 30 mm from the injection point as a function of ratio of water velocity at injection orifice to the air velocity in central pipe before the mixing chamber (d_w= 0.2 mm p_c= 6 bar)

Results of the simulations indicate that for the investigated range of parameters (air velocity 10, 20, 30 m/s, water velocity 1, 2, 3 m/s; orifice diameter 0.2 – 1 mm, pressure 3, 6 bar) relation of the water velocity at the orifice to the air velocity in the central duct which ensures correct structure of the jet varies. It mainly depends on the water orifice diameter, pressure within the mixing chamber, and the chamber diameter, as well as water injection angle. According to the simulation results, value of the searched velocity ratio varies from some 0.04-0.05 for a 1 mm orifice to ca. 0.1 for 0.2 mm orifice (diameter of the mixing chamber 6-10 mm, p_c = 6 bar).

Having identified the required ratio between the water velocity at the orifice and the air velocity in the mixing chamber for the assumed orifice diameter, it is possible to determine water velocity at a single orifice. This in turn enables to find liquid flow through single orifice.

This value in turn, combined with the assumed liquid flow m_L enables to determine the number of orifices. If the obtained number seems questionable (too high or low from technical point of view), the diameter needs to be changed and the process needs to be repeated. Based on our own experience the authors suggest to use diameters d_w within range 0.6-1 mm in order to avoid operational problems, e.g. with clogging. Orifices should be uniformly distributed along the circumference of the mixing chamber.

3. EXPERIMENTAL VERIFICATION

In order to verify the correctness of the presented design procedure, an atomiser was built with a geometry and operating parameters determined using this process. The characteristic parameters of the atomiser are as follows:

- nominal liquid flow m_L – 20 kg/h;
- mixing chamber diameter d_c – 6 mm;
- nozzle exhaust diameter d^* – 2.5 mm;
- diameter (d_w) and number of orifices (n) supplying water: 1 mm, 8;
- minimum mixing chamber pressure – 4 bar(a);
- minimum air flow m_A – 9 kg/h.

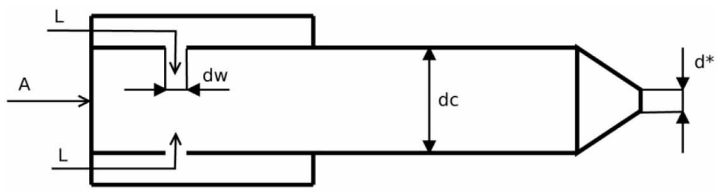

Fig. 3. Schematic diagram of an atomiser with characteristic dimensions marked

The first step of the experimental testing involved verification of compliance of the measured parameters with the calculated data obtained for exhaust nozzle diameter. The measured values included the liquid flow, air flow and mixing chamber pressure. The required nozzle diameter was calculated from these values. The measurement results are shown in Table 2.

Table 2. Exhaust nozzle diameter d^* calculated from the measurement results

Measurement number	Mixing chamber pressure [bar]	Water flow [kg/h]	Air flow [kg/h]	ALR [kg/kg]	Calculated diameter of the exhaust nozzle d^* [mm]
1	4	20	9.35	0.47	2.55
2	5	20	12.33	0.62	2.50
3	6	20	15.26	0.76	2.47

Nozzle exhaust diameter d^* calculated from the measurement results is complaint with the value used during measurements, i.e. 2.5 mm. This confirms that the presented calculation scheme is correct in this context.

The results of the measurements of the average droplet diameter obtained from the designed atomiser are presented below. The measurements were performed at a laboratory stand located at the Institute of Heat Engineering, Warsaw University of Technology, using a specialised equipment for determining the droplet diameters distribution in a two-phase flow Spraytec made by Malvern company. The monitored parameter was the Sauter Mean Diameter.

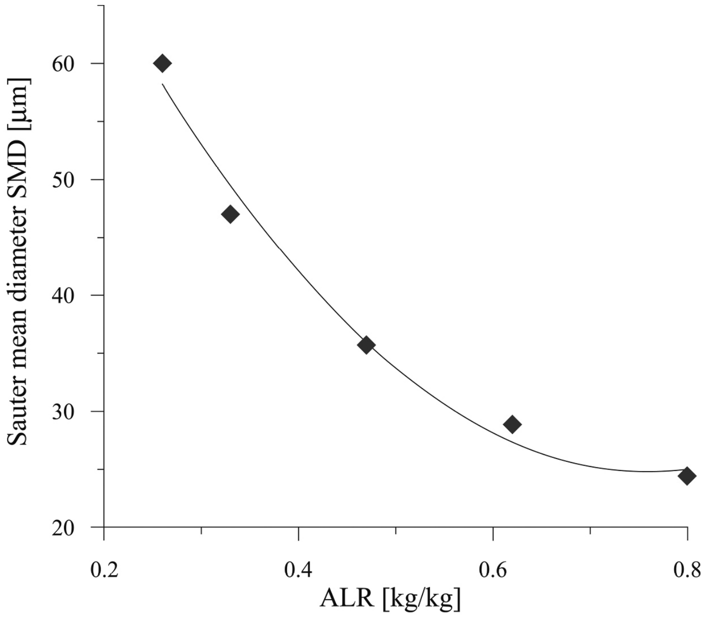

Fig. 4. Mean diameter of droplets of dispersed spray as a function of ALR

Analysis of data presented in Fig. 4 leads to a conclusion that quality of atomisation achieved in the designed equipment considerably depends on the amount of air supplied to the atomiser. The higher the air-to-liquid ratio, the lower the diameter of droplets in the spray. This conclusion seems to be consistent with the literature (Li et al., 2012; Watanawanyoo et al., 2011; Yudav and Kushari, 2011). According to the performed calculations, in order to maintain a desirable dispersive flow character in the designed atomiser, the air-to-liquid ratio should be not lower than 0.46. The measurement data reveals considerable reduction of the mean droplet size after exceeding that ALR value.

4. CONCLUSIONS

As already mentioned, the available procedures for designing liquid-to-air atomisers are based on certain simplifications and assumptions and do not allow precise determination of the liquid droplet size upon atomisation. For this reason it is ultimately not possible to determine desirable operating point of the atomiser without experimental testing. The presented approach, provided the original assumptions are kept, enables to determine certain geometric and operating parameters of an atomiser for required flow of sprayed liquid. It is based on the results of research on the two-phase flows and own analysis involving computational fluid dynamics. The results of laboratory testing of an atomiser unit designed according to the presented procedure confirm that the method for determining required exhaust nozzle diameter or minimum pressure in the mixing chamber yield correct results. They also reveal clear drop of an average volumetric-surface diameter d_{32} of droplets (i.e. better atomisation) obtained upon exceeding certain minimum air-to-liquid ratio as indicated by calculations. Liquid-to-gas atomisers are currently subject to intensive research by the authors of the paper.

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SYMBOLS

A	cross-section area, m^2
ALR	air to liquid ratio, kg/kg
c	speed of sound, m/s
D	diameter, m
G	mass velocity, $kg/(s \cdot m^2)$
m	mass flow rate, kg/s
n	number of orifices supplying water
p	pressure, Pa
k	isentropic exponent
M	Mach number,
R	individual gas constant, $kJ/(kg \cdot K)$
T	temperature, K
Q	volumetric flow rate, m^3/s
v	velocity, m/s

Greek symbols

α	volumetric air fraction
λ	coefficient
ρ	density, kg/m^3
ψ	coefficient
σ	surface tension N/m
μ	viscosity, $Pa \cdot s$

Superscripts

*	exhaust nozzle cross-section

Subscripts

A	*air*
c	mixing chamber
g	gas
L	liquid
st	normal conditions
w	water

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