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Condition Monitoring for Twin-Fluid Nozzles with Internal Mixing

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Abstract**—**Liquid sprays of water are frequently used in air pollution control for gas cooling purposes and for gas cleaning. Twin-fluid nozzles with internal mixing are often used for these purposes because of the small size of the drops produced. In these nozzles the liquid is dispersed by compressed air or another pressurized gas. In high efficiency scrubbers for particle separation, several nozzles are operated in parallel because of the size of the cross section. In such scrubbers, the scrubbing water has to be re-circulated. Precipitation of some solid material can occur in the liquid circuit, caused by chemical reactions. When such precipitations are detached from the place of formation, they can partly or totally block the liquid flow to a nozzle. Due to the resulting unbalanced supply of the nozzles with water and gas, the efficiency of separation decreases. Thus, the nozzles have to be cleaned if a certain fraction of blockages is reached. The aim of this study was to provide a tool for continuously monitoring the status of the nozzles of a scrubber based on the available operation data (water flow, air flow, water pressure and air pressure). The difference between the air pressure and the water pressure is not well suited for this purpose, because the difference is quite small and therefore very exact calibration of the pressure measurement would be required. Therefore, an equation for the reference air flow of a nozzle at the actual water flow and operation pressure was derived. This flow can be compared with the actual air flow for assessment of the status of the nozzles.

Keywords**—**Twin-fluid nozzles, operation data, condition monitoring, flow equation.

I. INTRODUCTION

LIQUID sprays are used widely for various purposes. If a small size of the drops produced is required, twin-fluid nozzles are usually applied. In twin-fluid nozzles, the liquid is dispersed by a pressurized gas. For example, viscous heavy fuel oil can be dispersed by twin-fluid nozzles to ensure better combustion [1]. Twin-fluid nozzles are also used for spraying of herbicides and fungicides in agriculture [2]. Another field of application of twin-fluid nozzles is the dispersion of viscous liquids and suspensions, for example paints [3], [4] or bitumen [5]. In the process industry liquid sprays are frequently used for the cooling and cleaning of gas streams [6]-[9].

For the separation of fine particles, twin-fluid nozzles with external or internal mixing can be applied [10]-[13]. External mixing twin-fluid nozzles traditionally have the liquid supply in the center and the atomizing gas supplied concentrically. The operation of such nozzles is simpler because the liquid flow and the gas flow can be controlled independently. Thus, the gas-to-liquid ratio (GLR) can be adjusted either by adapting the liquid flow or the gas flow. However, owing to the small flow cross sections, operation of these nozzles with solids-containing circulating water is not recommended. Some designs of twin-fluid nozzles with internal mixing, on the other hand, are more robust and have therefore been installed in scrubbers for dust separation [11]-[13].

The operation point of such a twin-fluid nozzle is usually defined by the required liquid flow rate, whereas the gas flow is mainly responsible for the size of the drops produced. Fig. 1 shows the operation curve of such nozzles schematically.

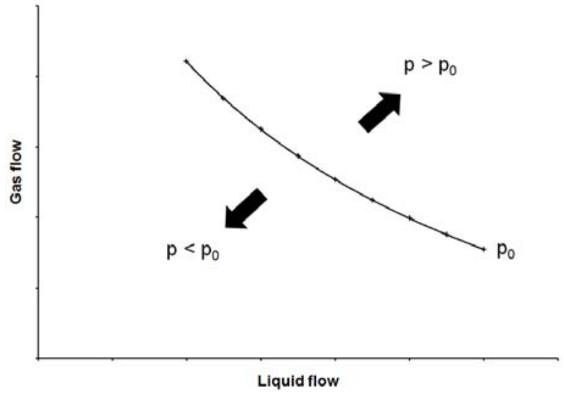

Fig. 1 Typical operation curve of a twin-fluid nozzle with internal mixing

The gas flow rate and the liquid flow rate of a nozzle with internal mixing are interdependent. In the operation of such nozzles the liquid flow rate and pressure of the gas are usually controlled.

Twin-fluid nozzles with internal mixing are used for example in high efficiency scrubbers for particle separation [9]-[13]. Because of the size of industrial scale scrubbers several nozzles are usually operated in parallel. The separation efficiency of the system is mainly influenced by the off-gas volume flow, the dust concentration and some dust properties like particle size and chemical composition. To secure the dust outlet concentration limit, the operation pressure of the nozzles is controlled. The higher the required separation efficiency, the higher is the required operation pressure. The water flow has to be adapted by the operator to influence the compressed air consumption to keep the centrifugal compressor supplying the compressed air in its range of operation.

In industrial scrubbers the scrubbing water usually has to be re-circulated. Precipitation of some solid material caused by chemical reactions can happen in the liquid circuit. During

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operation of the scrubber such precipitations can be detached from the place of formation. When they are transported to the nozzles they can partly or totally block the liquid flow through a nozzle. Because of the controlled liquid flow rate the liquid flow at the other nozzles increases slightly, thus decreasing the gas flow at these nozzles. In contrast, the gas flow through the blocked nozzle will be much higher, thus increasing the overall gas flow. Due to the unbalanced supply of the nozzles with water and air, the efficiency of the separation decreases. To compensate for the reduced efficiency, the operation pressure has to be increased. However, the operators do not have sufficient information about whether the required increase in the operation pressure is a result of reduced separation efficiency caused by blocked nozzles or whether it is the consequence of changing dust properties. If a certain fraction of blocked nozzles is reached the nozzles have to be cleaned.

The aim of this study was to develop a calculation tool that enables continuous monitoring of the status of the nozzles. It was a prerequisite to use only the measured operation data (water flow, air flow, water pressure and air pressure). In a twin-fluid nozzle with internal mixing the difference between the air pressure and the water pressure is usually quite small. Therefore, this difference is not well-suited for monitoring the nozzle status because very exact calibration of the pressure measurements would be required. Also the dependence of the pressure difference on the ratio of water flow to air flow would have to be considered. Therefore, the relative difference of the actual air flow $\dot{V}_{A,act}$ through a nozzle to the reference air flow $\dot{V}_{A,ref}$ through a clean nozzle at the actual water flow and actual air pressure $\Delta\dot{V}_{A,rel}$ according to (1) was chosen as the parameter for monitoring:

$$\Delta\dot{V}_{A,rel} = \frac{\dot{V}_{A,act} - \dot{V}_{A,ref}}{\dot{V}_{A,ref}} \tag{1}$$

To be able to calculate this difference, a function for the calculation of the reference air flow through a clean nozzle in dependence of the water flow and air pressure is required.

II. Material and Methods

A. Twin-Fluid Nozzles with Internal Mixing Investigated

A sectional view of the twin-fluid nozzle with internal mixing investigated is shown in Fig. 2. The nozzle outlet diameter d is 7.0 mm. In the tests, the liquid used was tap water and the gas was compressed air, both with a temperature of approximately 20 °C.

B. Nozzle Operation Curves

The air and water flow through a nozzle were measured for the typical operation range of the air pressure from 4.0 bar(g) to 6.0 bar(g). The variation range for the water flow was approximately 1:2. The results of the measurements are summarized in Fig. 3. The air volume flow is given at standard conditions (STP).

Fig. 2 Sectional view of a typical twin-fluid nozzle with internal mixing used for dust separation

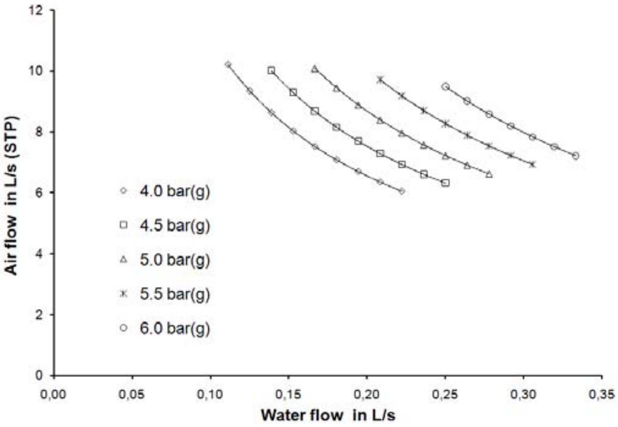

Fig. 3 Operation curves of the twin-fluid nozzles investigated

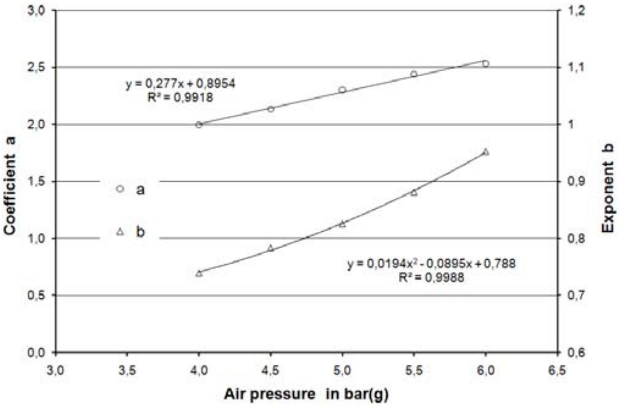

Fig. 4 Parameters of the approximation functions

III. Results

A. Mathematical Function for the Air Flow

For each operation pressure an approximation function for the air flow $\dot{V}_A$ in dependence of the water flow $\dot{V}_W$ of the type of (2) was derived:

$$\dot{V}_A = a \cdot \frac{1}{\dot{V}_W^{\,b}} \tag{2}$$

The parameters of these functions are summarized in Fig. 4. The correlation coefficient r² was higher than 0.99 for each approximation function.

For the dependence of both parameters on the air pressure p_A^* (in bar(g)) an approximation function was derived. Inserting these functions into (2) resulted in (3) for the air flow through a clean nozzle in dependence of the water flow and the air pressure:

$$\dot{V}_A = \frac{\left(0.277 \cdot p_A^* + 0.8954\right)}{\dot{V}_W^{\left(0.0194 \cdot \left(p_A^*\right)^2 - 0.0895 \cdot p_A^* + 0.788\right)}} \tag{3}$$

B. Verification with Scrubber Operation Data

For verification of the formula, the results were compared with operation data of a scrubber with 676 nozzles installed in parallel. For use of (3) for a scrubber with n nozzles in parallel and because of different units for the total air flow and the total water flow the equation has to be adapted (4):

$$\dot{V}_{A,ref} = 3.6 \cdot n \cdot \frac{\left(0.277 \cdot p_A^* + 0.8954\right)}{\left(\dfrac{\dot{V}_{W,act}}{3.6 \cdot n}\right)^{\left(0.0194 \cdot \left(p_A^*\right)^2 - 0.0895 \cdot p_A^* + 0.788\right)}} \tag{4}$$

In (4) $\dot{V}_{A,ref}$ is the total air flow in m³/h (STP) and $\dot{V}_{W,act}$ is the total water flow in m³/h delivered to the scrubber nozzles. The air pressure p_A^* has to be inserted in bar(g).

The following data were measured at the scrubber when it was operated with water and air with the nozzles still clean: air pressure of 3.79 bar(g), the water flow $\dot{V}_{W,act}$ of 454.5 m³/h and the air flow $\dot{V}_{A,act}$ of 15,714 m³/h (STP). Because of the clean nozzles $\dot{V}_{A,act}$ should be equal to $\dot{V}_{A,ref}$. The calculated value for the air flow $\dot{V}_{A,ref}$ according (4) is 16,045 m³/h (STP). Thus, the measured value was 2.1% lower than the calculated value.

C. Sensitivity of the Detection of Blocked Nozzles

As long as the pressure ratio of the pressure inside the scrubber to the pressure of the compressed air – both measured as absolute pressure – is lower than the critical pressure ratio, which is 0.528 for air [14], the air velocity at the nozzle outlet of a nozzle with a totally clogged water supply is equal to the sonic velocity. As the pressure inside the scrubber is typically close to the ambient pressure and the operation pressure of the nozzles p_A is typically in the range of 400,000 to 700,000 Pa(a) the pressure ratio is always below the critical value. Thus, the mass flow of air through the nozzle $\dot{m}_{A,c}$ is given by (5) [13]:

$$\dot{m}_{A,c} = \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot C_d \cdot A \cdot \sqrt{\frac{2 \cdot \kappa}{\kappa+1} \cdot p_A \cdot \rho_A} \tag{5}$$

The isentropic exponent κ of air is 1.4. For the discharge coefficient C_d of the nozzle a value close to 1.0 can be assumed [15]. In the calculation a value of 0.95 was used. The air density ρ_A depends on the density of air at standard conditions $\rho_{A,N}$ (1.29 kg/m³) and the pressure and the temperature of the air.

The air flow through a nozzle with a totally clogged water supply $\dot{V}_{A,c}$ (in m³/s (STP)) can be calculated by dividing the mass flow by the density of the air at standard conditions. When the actual density ρ_A is expressed by the standard density, (6) results:

$$\dot{V}_{A,c} = \frac{1}{\rho_{A,N}} \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot C_d \cdot \frac{d^2 \cdot \pi}{4} \cdot \sqrt{\frac{2 \cdot \kappa}{\kappa+1} \cdot p_A \cdot \rho_{A,N} \cdot \frac{p_A \cdot T_{A,N}}{p_{A,N} \cdot T_A}} \tag{6}$$

When c is the number of nozzles with totally clogged water supply the calculated air flow through a full scale scrubber with n nozzles can be calculated using (7):

$$\dot{V}_{A,scr} = \frac{3.6 \cdot (n-c) \cdot \left(0.277 \cdot p_A^* + 0.8954\right)}{\left(\dfrac{\dot{V}_{W,scr}}{3.6 \cdot (n-c)}\right)^{\left(0.0194 \cdot \left(p_A^*\right)^2 - 0.0895 \cdot p_A^* + 0.788\right)}} + 3600 \cdot c \cdot \dot{V}_{A,c} \tag{7}$$

For the operation point of the scrubber mentioned above the relative increase in air flow was calculated for various fractions of nozzles with totally clogged water supply. The results are shown in Fig. 5. When 1% of the nozzles are clogged the increase in air consumption is approximately 3%. Thus, even a small fraction of clogged nozzles can be indicated by the method developed.

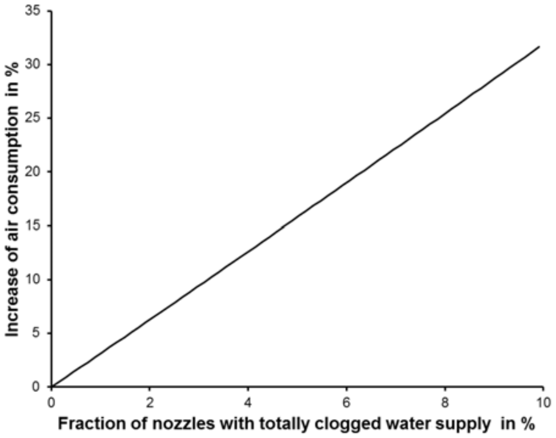

Fig. 5 Relative increase in air flow as a function of the fraction of nozzles with totally clogged water supply

IV. CONCLUSION

With the new method based on the formula for the nozzle airflow derived from nozzle measurements deviations in nozzle operation starting from approximately 1% of totally clogged nozzles can be detected without disturbing scrubber operation. Continuous monitoring of the twin-fluid nozzles is now possible with this method.

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