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An Analysis of the Bi-modal Size Distribution of the Coarse Droplets in a Steam Turbine

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Abstract. The atomization of liquid is a widely studied problem in the field of aerosol research. Over the past year, research at CTU has focused on the formation of coarse droplets in a wind tunnel which simulates the conditions present in a steam turbine. An analysis of the droplets formed in the wind tunnel indicates, for the majority of the measurements, the bi-modal droplets size distribution. The aim of this paper is to suggest a simplified explanation of this bi-modal distribution. The CFD simulation of the flow in the vicinity of the liquid film break up was used to determine the relative velocity between the formed droplet and the bulk flow. The preliminary explanation of the bi-modal distribution is based on the first droplets mode corelating with the formation in the bulk flow and the second mode correlating with the droplets formed in the blade's wake.

1 Introduction

The liquid film atomization is an important technical problem in many practical applications, but a general theoretical description of the whole process is still absent. Water film atomization can also be found in low pressure parts of steam turbines. The coarse water droplets are formed from the water film on the blades and casings. This process is connected to undesirable effects on the reliability and efficiency of steam turbines [1, 2]. Related effects such as additional energy losses, blade erosion or the reduction of the blade's lifetime can be further noted. The study of liquid atomization, movement and its potential impact of the formed droplets on the moving blades in turbines at high speed has an important role in the never-ending effort to enhance energy production efficiency and to decrease its environmental impact.

Two populations of droplets are present in steam turbines. Fine droplets are formed by nucleation and condensation as expanding steam passes the saturation line. These fine droplets fall mostly within a diametral range of 0.1 – 1 μm. These fine droplets are transported, mostly by turbulent diffusion, on the blades and casings. Subsequently, the captured droplets can create a liquid film which tears off in the form of coarse droplets. The expected diametral range of coarse droplets in steam turbines ranges between 1 μm to 1 mm. The measurement of the size distribution function of the coarse droplets in the nozzle shows

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the bi-modal function of the coarse droplets. The aim of this contribution is to suggest some explanation of this phenomena.

2 Droplet formation

The following chapter is devoted to the analysis of the liquid film breakup. The current theory is based on the works of Rayleght, Weber and Ohnesorge [4]. The theory suggested several regimes of liquid film atomization. One can distinguish high-speed liquid breakup among Rayleight-type, Membrane-type and Fiber-type atomization. The photogrammetric measurements carried out in the wind tunnel show that the atomization of the trailing edge of the profile is very stochastic and may be visible in all of these atomization modes (Fig.1).

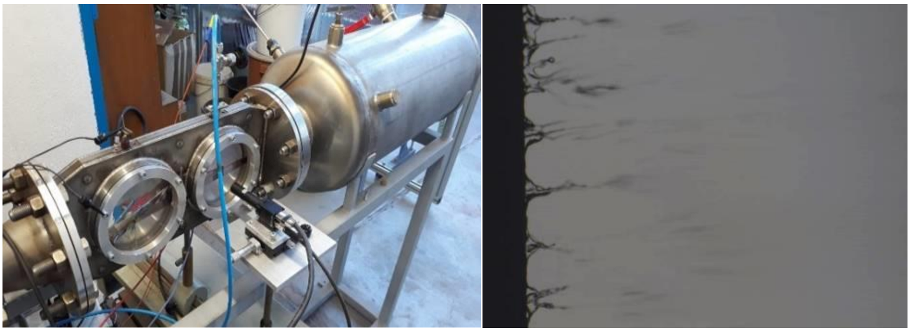

Fig. 1. The wind tunnel and the water film breakup on the trailing edge of the blade.

The mentioned theoretic modes are described by the non-dimensional Weber number as defined by:

$$We = \frac{\rho_g {w_r}^2 d}{\sigma} \tag{1}$$

where (ρ_g) is vapour density, (σ) is surface tension of the water, (w_r) is the relative velocity between the vapour and the droplets and (d) is the diameter of the droplets.

For the above-mentioned reason, the description of the “chaotic” atomization is still not sufficient. One of the possible parameters which can be determine is the maximum droplet diameter as defined by the critical Weber number We_{crit}. The critical Weber number is the non-dimensional ratio between drag forces and surface tension. The critical value is not constant for any cases, but for the low-viscosity liquid suddenly exposed in the high velocity air steam was estimated We_{crit}=13 [3, 4]. It is necessary to note that there are more values for We_{crit} in literature in a range of 10-40 [1, 3].

3 Measurement

The experiment was carried out in the wind tunnel with two blades possessing differing surface properties that are placed in the air flow. The first blade was coated with electrical insulating and hydrophobic paint and the second was polished stainless steel. The overall view of the tunnel is in Fig. 1.

3.1 The wind tunnel

The motivation for the wind tunnel assembly arose from a previous measurement [6] of the coarse droplets in the steam turbine under operational conditions. The measurement was performed in three steam turbines in Czechia. The amount of the acquired coarse droplets was very low due to their low number density level. Due to difficulties connected with measurements in an operating steam turbine, a wind tunnel was designed and manufactured for the analysis of the coarse droplet formation from the liquid films. The aim of the design was to create, as closely as possible, the conditions in a steam turbine while utilising the advantages of working in the laboratory.

The wind tunnel is designed as a classical CD nozzle, but the planned operational regime is mainly subsonic or transonic. An aerofoil NACA0008 is placed 50 mm behind the nozzle throat. The aerofoil simulates the blade in the turbine, and it is possible to remove or replace it. There is a groove on the aerofoil which supplies liquid to the surface. The liquid is pumped to the aerofoil through the dosing pump with a flow between 1 ml/min to 500 ml/min. The tunnel is equipped with four large optical windows that provide good visual access for the measurements. It is possible to operate the tunnel with steam in a continuous mode or with compressed air in a periodic mode.

3.2 The size distribution measurement

The droplet distribution function measurement was performed on a Spraytec instrument (Malvern, Inc.). Both blades were tested under the same conditions in the wind tunnel. The measuring position of the laser beam was about 20 cm behind the trailing edge of the blade. Due to the principle of measurement (scattering of light on the droplets), the conditions for evaluation were not always met, therefore the results are calculated only for the states when the conditions for evaluation were acceptable. In Fig. 2, the volumetric or mass fraction distribution is shown. It is possible to observe the bi-modal distribution.

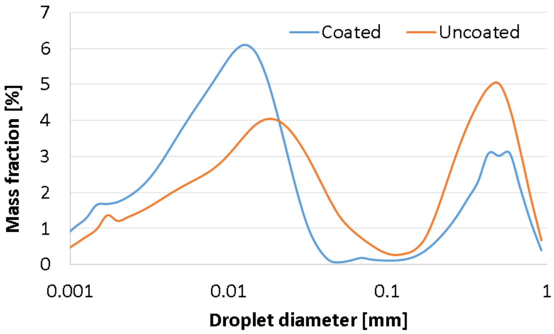

Fig. 2. Mean size distribution of the droplets for both blades.

4 Data processing

4.1 Droplet analysis

The collected data of the size distribution function of the droplets were divided into two groups and the Sauter mean diameter was computed for both of them. The edge diameter between the small and large droplets was estimated at 60 µm (approximate saddle between the modes).

$$D_{32} = \frac{\sum d^3}{\sum d^2} \tag{2}$$

Table 1. contains six values of the Sauter mean diameter for three measurements of coated and three measurements of uncoated blades. The Sauter mean diameter is used for comparing each separate measurement. The rate is the mass ration between small and big droplets. The introduced distributions are representative examples of the typical measurement.

Table 1. Sauter mean diameter and the droplet rate.

	Diametre D32		Mass rate	
	Small [µm]	Big [µm]	Small [%]	Big [%]
Coated 1	5.3	386.2	72.4	27.6
Coated 2	5.0	458.8	88.3	11.7
Coated 3	4.8	353.3	75.6	24.4
Uncoated 1	7.9	332.2	59.8	40.2
Uncoated 2	5.8	136.8	75.9	24.1
Uncoated 3	5.2	209.4	84.2	15.8

4.2 Flow field

Information regarding the relative velocity in the vicinity of the trailing edge is not possible to measure directly. The local velocity from the CFD simulation is used to determine the relative velocity in order to calculate the Weber number. The velocity of the liquid film is expected to be negligible. A mesh with 1 114 764 polyhedral cells with a prismatic boundary layer was created. This mesh had an increased density near the NACA profile. SST k-ω model of turbulence was used for the simulation. Pressure boundary conditions were used, both at the inlet and outlet. The inlet pressure was known accurately. However, the outlet pressure was less exact since the flow exiting from the nozzle enters the pipe system before exiting into the atmosphere. The outlet pressure was considered atmospheric (101 325 Pa) assuming that the pressure losses in the pipe system are negligible. The details of the simulation are recorded in [7].

Fig. 3 and Fig. 4 show the velocity of the flow both along and perpendicular to the blade respectively.

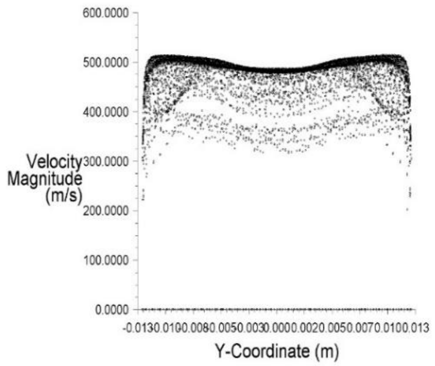

Fig.3. Velocity profile for the Y coordinate (along the channel trailing edge of the profile)

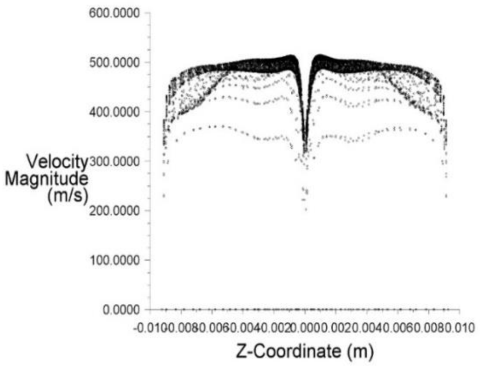

Fig. 4. Velocity profile for the Z coordinate (perpendicular to the channel)

5 Results

The bulk flow in the nozzle is generally transonic. As is possible to see in Fig. 5 and Fig. 6 close to the profile's trailing edge the flow velocity is approximately 300m/s. The critical Weber number describes the maximum droplet diameter, for the analysis the D_{95} was used. The value D_{95} is the diameter for which 95% by mass is contained in the smaller diameter. In Table 2. are written values of D_{95} and Weber numbers for the group of small droplets. The total mass fraction of these droplets is around 75% (Table 1.). The rest of the droplet mass is represented by the small number, at least 3 orders of magnitude, of droplets with big diameter D_{32} is around 200-300μm and D_{95} is around 0.5mm. The existence of these droplets has to be explained. The process of the liquid film is stochastic and also the flow of the carrier gas around the obstacle is connected with the wake and turbulence. On Fig. 5 and Fig. 6 is shown the turbulence intensity and velocity in the channel.

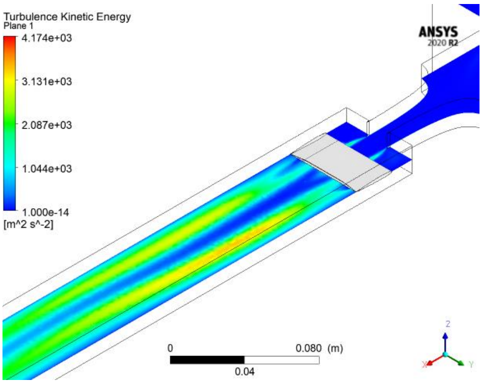

Fig. 5. Turbulent kinetic energy in the channel.

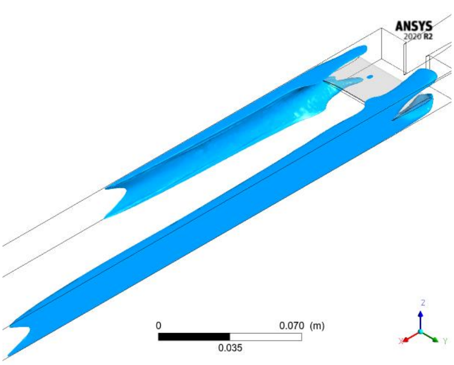

Fig. 6. Velocity areas lower than 60 m/s.

The CFD computation provides the statistical mean velocity, and the random fluctuations are possible to estimate according to kinetic energy turbulence. For the purpose of this paper, a reverse logic was utilised. The value of the local velocity fluctuation was found to meet a Weber number similar to the small droplets (We ≈ 40) and, together, the velocity from the turbulent kinetic energy. The estimated value $w_r = 60$ m/s was suggested. The Weber numbers for the big droplets with diameter D_{95} are shown in Table 2. One can expect that this part of the water went to the vortex region with a smaller relative velocity and is accelerated slowly. This leads to satisfying the Weber theory, although the droplet is bigger than it should be.

Table 2. Table of the D_{95} for both droplet modes and the values of We at different velocities.

	Droplet diameter D_{95} [μm]		We (300 m/s)	We (60 m/s)
	small	large	small	large
Coated 1	23	500	44	38
Coated 2	12	500	22	38
Coated 3	20	580	37	44
Uncoated 1	32	580	59	44
Uncoated 2	20	200	37	15
Uncoated 3	10	430	19	32

6 Conclusions

The process of liquid atomization from the liquid film on the obstacle in transonic flow is an extremely complex problem. The purpose of this paper is not to explain all the details of the liquid atomization or to provide a detailed study of the flow field. The main aim is to suggest an explanation relating to the second mode of the droplet's existence in the size distribution function. The influence of the different blade's coating is not significant, but there is a small improvement for a coated blade because the number of large droplets is slightly lower [8]. The result of the paper can help to better understand the erosion processes in the steam turbines, as well as, in other technical applications. Future research incorporating detailed analysis is still necessary.

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