Spray Atomization Simulation of Bamboo Kraft Black Liquor with High Solid Content at Splash-plate Nozzle

Yongjian Xu,[a,b,c,d,]* Shenglin Chen,[a] Xin Du,[a,b] and Xiaopeng Yue [a,b,c,d]

Increasing the solids content of pulping black liquor burned in a furnace is a development trend of the alkali recovery system in the pulp and paper industry. However, the viscosity of kraft black liquor increases exponentially with an increase in solids content, especially in the case of non-wood pulping black liquor, such as bamboo. This brings great difficulties to the pulping system and atomization of black liquor at the splash-plate nozzle, which is a complete atomization unit constituted of a splash nozzle and a splash plate. To obtain instructive results for industry, a simulation of the atomization process was made using Fluent software for the bamboo kraft black liquor with solids contents of 70 wt% and 80 wt%, which flowed through splash nozzles with the diameter of 22 or 20 mm. The studies were conducted on the distribution of flow field in the nozzle and atomization region through changing the injection pressure and nozzle diameter. The variation of atomization characteristic parameters, such as liquid film thickness, and breakup length, were elucidated. The results reveal the relationship between spray atomization with injection pressure and nozzle diameter, which provides a theoretical basis for improving the concentration of black liquor entering alkali recovery in the future.

Keywords: Atomization simulation; High solid content; Fluent software; Splash-plate nozzle; Bamboo kraft black liquor

Contact information: a: College of Bioresources Chemical and Materials Engineering, Shaanxi University of Science & Technology, Xi'an, Shaanxi Province, 710021,China; b: Key Laboratory of Paper Based Functional Materials, China National Light Industry; c: Shaanxi Provincial Key Laboratory of Papermaking Technology and Specialty Paper Development; d: National Demonstration Center for Experimental Light National Demonstration Center, Xi'an, Shaanxi Province, 710021, China;
** Corresponding author: xuyongjian@sust.edu.cn*

INTRODUCTION

Kraft black liquor is a waste stream from the pulping industry produced during kraft pulping, consisting of complex organic and inorganic compounds. An alkali recovery system is able to dispose of wood pulping black liquor more efficiently and environmentally than acid-precipitation method or coagulation method. In the alkali recovery system, the kraft black liquor is evaporated and concentrated to a solids content of more than 70 wt%, and then it is pumped into the alkali recovery furnace for heat and chemical recovery through combustion. But there are some difficulties to be dealt with for non-wood pulping black liquor (*i.e.*, bamboo kraft black liquor (BKBL)) due to the high silicide content, which accounts for more than 60% of ash in non-wood raw materials (Matalkah *et al.* 2016). The silicide in raw materials reacts with alkali to produce Na_2SiO_3 dissolved into the black liquor, which will cause a series of trouble, named "silicon interference" problems. One of the problems is that the viscosity of BKBL will increase rapidly with the increase in silicon content, which brings problems to black liquor pumping and atomization and then has an influence on the evaporation and combustion efficiency (Zaman and Fricke 1996; Liu *et al.* 2013; Xu *et al.* 2016a, 2016b). The black liquor forms a liquid film when hitting the splash-plate nozzle at a higher speed by accelerating in the barrel of spray gun, and this process is defined as an atomization (Barreras *et al.* 2006). The liquid film is progressively broken up into strips, drops, and finally fine particles (Sarchami and Ashgriz 2010; Sarchami and Ashgriz 2011). The purpose is to increase the evaporation surface area and strengthen the mixing of black liquor and combustion supporting air to ensure that black liquor can be dried and carbonized rapidly and completely in the furnace.

With the development of computer software and hardware, numerical simulation technology has developed rapidly and is applied in many fields. Wang *et al.* (2019) used numerical simulation method to study the combustion difference of single biomass particle in O_2/N_2 and O_2/CO_2 atmosphere; Xu *et al.* (2019) determined the best atomization condition of the spray dust reduction device in the coal mining process; Hou *et al.* (2018) studied the heat transfer characteristics of nozzle spray cooling; and Lee *et al.* (2002) carried out an experimental and numerical study on the macro spray structure and spray characteristics of a diesel common rail high pressure injector. In addition, the numerical simulation technology is also applied to the simulation of black liquor atomization and combustion. Levesque *et al.* (2005) developed a program to simulate the process of black liquor atomization; Sarchami *et al.* (2009) determined the functional relationship between black liquor properties and nozzle shape; Cardoso *et al.* (2012) analyzed the performance of black liquor recovery boiler with simulation software "wingms"; and Bhargava *et al.* (2008) established a mathematical model to simulate the evaporation process of black liquor.

Fluent software is based on the mass conservation, momentum conservation, and energy conservation equations to calculate and solve for fluid flow. Various flow patterns, such as laminar and turbulence flows, should be considered in the practical calculation and model selection. The spray atomization of black liquor includes the mixed flow state of air phase and black liquor phase, which belongs to the subject of multiphase flow. In this study, the “volume of fluid” (VOF) model in fluent software was used to simulate the mixing atomization of air and black liquor by solving the separate momentum equation and calculating the volume fraction of black liquor passing through splash-plate nozzle, which could predict the breakup of black liquor jet and the position change in bubbles in the liquid.

Foust *et al.* (2002) used the VOF model to simulate the process of black liquor broken up into droplets through splash-plate nozzles, discussed the influence of nozzle shape, and black liquor flow rate on the droplet size and flow distribution. They also analyzed the distributions of pressure field, air flow field, and turbulent kinetic energy of black liquid droplets in the furnace. Liu (2015) applied the VOF model to simulate the atomization process of black liquor passing through pressure swirl atomizer, and studied the influence of pressure, structure size, and different initialization methods on the atomization characteristics of black liquor. The same model was used by Hasanpoor *et al.* (2011) in the simulation software to simulate the evaporation process in two-phase flow based on the consideration of energy and mass transfer in the process of phase transformation, and studied the two-phase characteristics such as gas holdup, wall temperature distribution, heat transfer coefficient, and heat flow density.

The atomized mixture is composed of air and the fine particles produced during the atomization of black liquor. The air is the first phase (main phase) and the black liquor is the second phase (q-phase). Assuming that the volume fraction of q-phase in the control unit is α_q, when α_q equals to 0, there is no q-phase fluid in the unit; when α_q equals to 1, the unit is filled with q-phase fluid; when αq is greater than 0 and less than 1, the unit contains the interface of q-phase fluid and one or other multiphase fluid.

Volume fraction equation (continuity equation)

The VOF model tracks the interface between phases by solving the continuous equation of the volume fraction of one or more phases. The equation is as follows for the q-phase,

$$\frac{1}{\rho_q}\frac{\partial(\alpha_q\rho_q)}{\partial t}+\frac{1}{\rho_q}\bullet\nabla(\alpha_q\rho_q\upsilon_q)=\frac{S_{\alpha_q}}{\rho_q}+\frac{1}{\rho_q}\sum_{p=1}^{n}(m_{pq}-m_{qp}) \tag{1}$$

where α is phase volume fraction, ρ is density (kg/m^3), v is velocity (m/s), m_{pq} is mass transfer (kg) from p-phase to q-phase, and $S_{\alpha q}$ is a quality source term. The general default is 0.

Momentum equation

In the process of atomization, the existence of surface tension makes the surface area of droplets always tend to be minimum. The surface tension model in Fluent is set as following equation,

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla(\rho\vec{v}\vec{v})=-\nabla p+\nabla\bullet\left[\mu(\nabla\vec{v}+\nabla\vec{v}')\right]+\rho\vec{g}+\vec{F} \tag{2}$$

where ρ is density (kg/m^3), μ *i*s dynamic viscosity (Pa · s), $\vec{F}$ is original term of interface force (N/m^3), and $\vec{v}$ is velocity (m/s).

At present, BKBL with the of 70 wt% solid content is usually atomized at the splash-plate nozzles with the internal inner diameters of 20 and 22 mm, where the spray atomization can normally and stably operate under the pressure of 120 and 150 kPa. This has laid a good foundation for the highly efficient operation of alkali recovery furnace. However, if the solid content of black liquor is further increased up to 80 wt%, the obvious increase in its viscosity and surface tension will certainly have a great effect on the spray atomization of black liquor at splash-plate nozzles. Therefore, it is necessary to study the spray atomization performance of black liquor with a super high solids content. In order to overcome the limitation of experimental conditions to obtain the instructive results for industry, the authors' group used Fluent software to simulate the spray atomization of BKBL flowing through splash-plate nozzles by changing the injection pressure and internal diameter of splash nozzle, and further studied the flow field distribution in the splash-plate nozzle and atomization region. Finally, the variation rules were summarized for spray atomization characteristic parameters such as film thickness, breakup length, and spray cone angle.

EXPERIMENTAL

Establishment of Physical Model

The splash-plate nozzles with the diameters of 20 or 22 mm, mainly equipped in alkali recovery furnaces, were used to simulate the flow and spray atomization of black liquor. It is necessary not only to model the flow passage inside the splash nozzle, but also to model and mesh the atomization area when the black liquor flows out of the splash nozzle. SolidWorks software (SolidWorks, Dassault Systemes, v.2015, Waltham, MA, USA) was used to model the inner runner of the splash-plate nozzle and atomization region.

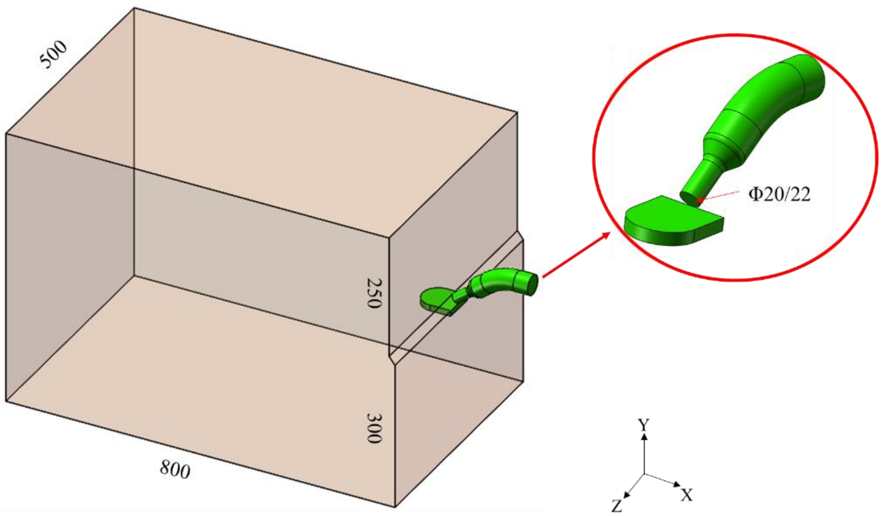

Fig. 1. The nozzle and atomization region model

Meshing

The integrated Mesh meshing module in ANSYS Workbench (ANSYS workbench, ANSYS, 16.0, Pittsburgh, PA, USA) can mesh complex geometry in a relatively short time. The geometric model was patched and sliced in the DesignModeler (Sub module of ANSYS software) modular at first, and then imported into Mesh (Sub module of ANSYS software) modular to divide high-quality meshes.

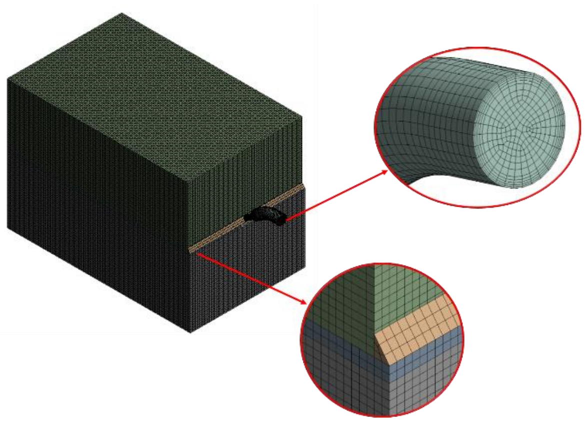

Fig. 2. The nozzle and atomization region model after meshing

Election of Numerical Models

Multiphase flow model

The black liquor is accelerated out of the splash nozzle, affecting the splash plate to break into a liquid film, which eventually is atomized into droplets. This process is a gas to liquid two-phase flow problem that involves tracing the change in the interface between gas (air) and liquid (black liquor). Therefore, the VOF model was used to simulate the spray atomization of BKBL with high solid content at the splash-plate nozzle.

Laminar flow model

The black liquor atomization was analyzed and compared with the laminar flow and standard models (Liu 2015). The result showed that an obvious atomization could be observed when using the laminar flow model, but not when using the standard k-ε model. It was speculated that the higher density and viscosity of black liquor might be responsible for that result. Thus, the turbulence had a negligible effect on the flow process. This is consistent with the fact that scholars Foust and others neglected turbulence in simulating black liquor atomization (Foust *et al.* 2002). Therefore, the laminar flow model was judged to be suitable and was utilized to simulate the atomization of BKBL with high solid content at splash-plate nozzle.

Setting of Simulation Parameters

Model setting

In the multi-phase flow model panel, the VOF model was chosen with the phase number set to 2, the implicit body force option was checked to improve convergence, and the rest remained the default. Air was set as the main phase and the black liquor as the auxiliary phase. The surface tensions of BKBL with high solid content according to the measured data are displayed in Table 1, and laminar flow model was opened.

Table 1. Physical Parameters of BKBL at 125 °C

Solid Content (wt%)	μ (Pa·s)	ρ (kg/m^3)	v (m^2/s)	Surface Tension (N/m)
70	0.2	1410	1.42×10^{-4}	0.06
80	0.35	1470	2.38×10^{-4}	0.065

(μ: dynamic viscosity; ρ: density; v: kinematic viscosity)

Boundary conditions

The inlet pressure was orderly set at 130, 140, 150, 160, and 170 kPa, based on the boundary conditions. The authors' group simulated the spray atomization effect of BKBL with the solid content of 70 wt% and 80 wt% separately flowing through 22 and 20-mm nozzles. In the above spray atomization process, the black liquor multiphase volume fraction was set to 1, which indicated that the black liquor was full of the inlet cross-section. Meanwhile, the outlet pressure boundary condition was set to 0 Pa. The detailed simulation scheme is presented in Table 2.

Solution settings

The "Pressure-Implicit with Splitting of Operato" (PISO) algorithm was used to solve the unsteady state and the interpolation method was set to "PRESTO!". The relaxation factor "Momentum" was set to 0.5 to improve the convergence and save computing time. The initial value of "black liquor volume fraction" was set to zero, indicating that the computational domain was filled with air in the initial state. Furthermore, in order to improve the stability of calculation, the maximum iteration time step was 1×10^{-4} s while the minimum was 5×10^{-5} s, and the total simulation time for black liquor flow was 0.1 s.

Table 2. Scheme of BKBL Atomization Simulation

Serial Number	Nozzle Diameter (mm)	Injection Pressure (kPa)	Solid Content (wt%)
Case1	22	130, 140, 150, 160, 170	70
Case2	22	130, 140, 150, 160, 170	80
Case3	20	130, 140, 150, 160, 170	70
Case4	20	130, 140, 150, 160, 170	80

RESULTS AND DISCUSSION

Atomization Process of BKBL at Splash-plate Nozzle

It can be observed that the simulated black liquor formed a thicker liquid film after impacting the splash plate at 0.02 s, as shown in Fig. 3. With extended time, the edge of liquid film gradually thinned and developed downstream, and then the front end (near the splash nozzle) of liquid film contracted into a ring at 0.04 s. After impacting for 0.05 s, the black liquor further broke into droplets. Collisions or mergers may occur alternatively during the backward movement of droplets, resulting in secondary atomization. This process fully complies with the atomization characteristics dominated by the edge-breaking mode (Schmelz and Walzel 2003; Li and Dinh 2004; Wang and Zhao 2018).

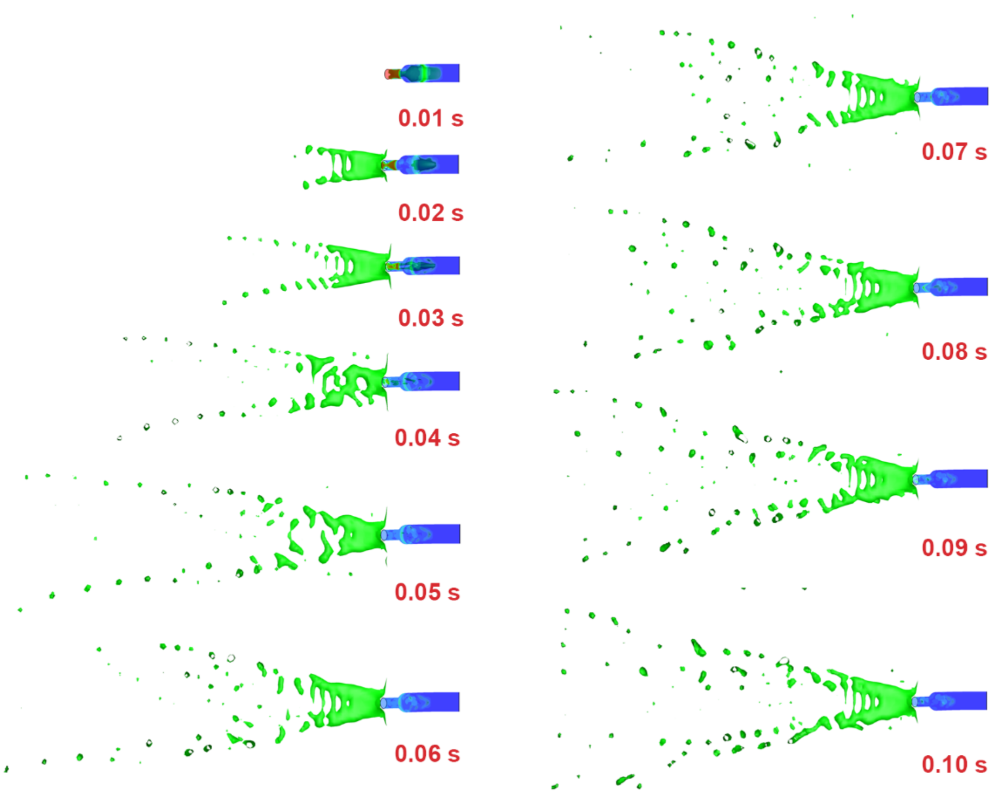

Fig. 3. The process of BKBL with 70 wt% atomizing into droplets at 130 kPa

Analysis of Flow Field Characteristics at Splash-plate Nozzle

A complete atomization unit consists of an integrally-built splash-plate nozzle comprising a splash nozzle and a splash plate. The function of the former is to eject the black liquor under high pressure, and the latter is to promote the development of the black liquor from columnar to liquid film and finally to liquid drops. The high speed black liquor flow out of the splash nozzle constantly impacts the splash plate during spraying, causing a serious abrasion of the splash nozzle and splash plate due to scouring with a long time. Therefore, the splash-plate nozzle has to be replaced integrally and regularly. This indicates that it is of great significance to study the pressure distribution on the splash plate plane for the structural design and material choice of splash nozzle. Figure 2 demonstrates the pressure distribution curves under different injection pressures at the nozzles with the inner diameters of 22 and 20 mm, respectively, when the solid content of BKBL is 80 wt%.

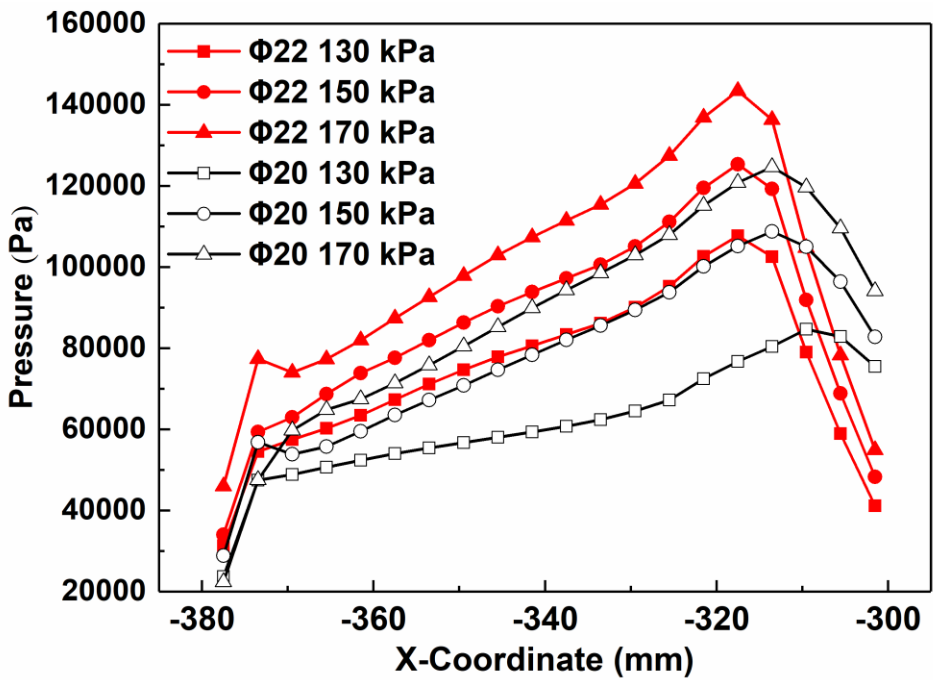

Fig. 4. Pressure distribution on splash plate axis (the coordinate origin is the joint of nozzle and splash plate)

It can be seen in Fig. 4 that the maximum pressure on the axis of splash-plate nozzle with different diameters was intensively produced in the range between -320 and -310 mm where the BKBL was gradually broken into liquid film. This means that the surface is heavily scoured at this location. When the injection pressure was the same, the maximum pressure on the splash plate decreased with a decrease in the nozzle diameter, and the position of the maximum pressure was closer to the splash nozzle. This suggested that the mass flow of black liquor decreased with a decrease in the nozzle diameter and the maximum injection pressure on the splash plate was smaller. Moreover, as the area of liquid film increased, the injection pressure on the splash plate gradually decreased, but slightly rebounded at - 372 mm, where the black liquor film might collide with the splash plate again and then was gradually broken up into droplets. This causes the lowest pressure locates on the left edge of splash plate.

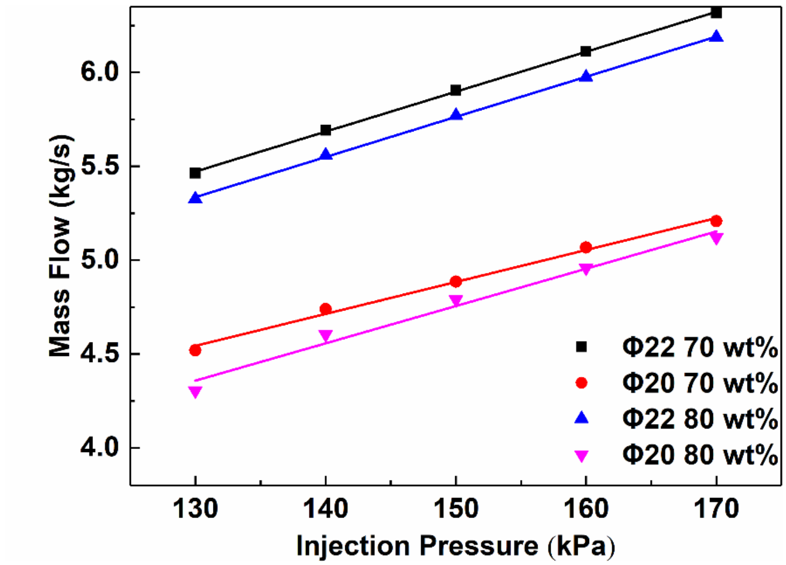

Fig. 5. Mass flow rate *vs.* injection pressure of nozzle outlet

Figure 5 shows that the mass flow rate of BKBL was a directly proportional increasing function to the injection pressure when the BKBL with the solid content of 70 wt% and 80 wt% was passing through the splash nozzle outlet with 22 and 20 mm diameters, respectively. The mass flow also increased with the increase in nozzle diameter under the same solid content levels. The mass flow rate of BKBL with 70 wt% solid content was a little bigger than that with 80 wt% solid content under the same injection pressure and nozzle diameter because the viscosity of the former was small. In addition, it can be inferred that the influence of viscosity is much bigger than that of density within the range of the solid content studied in this research.

Analysis of Flow Field Characteristics in Atomization Region

When the flow hits the splash plate at a high speed, the black liquor forms a continuous liquid film with a certain thickness that is perpendicular to its moving direction. Relevant literature (Kim *et al.* 2009) considers that the liquid film thickness has a direct relationship with the size of droplets after atomization. It has been shown that the thinner the thickness is, the smaller the droplet size, and display better the spray atomization effect (Rizk and Lefebvre 1980). Therefore, it is helpful for understanding the change rule of droplet size after atomization of BKBL with high solid content to analyze the thickness of liquid film on the splash plate.

Figure 6 displays the change in the liquid film thickness under various injection pressures. It can be seen that the larger the splash nozzle diameter, the bigger the liquid film thickness. This suggested that the mass and volume flow rate of the black liquor at the splash nozzle increase with the increase in the splash nozzle diameter, causing the flow of more black liquor on the splash plate per unit time. This suggests that the flow velocity of liquid film does not change much, which causes the increase in the thickness of liquid film near the splash nozzle. The change in the injection pressure had an approximate effect on the thickness of liquid film under the injection pressure range of 130 to 170 kPa at a 20-mm or 22-mm nozzle. There are two reasons for this: the narrow range of injection pressure changes the velocity slightly; and the large viscosity of black liquor restrains pronounced changes in the thickness of the liquid film.

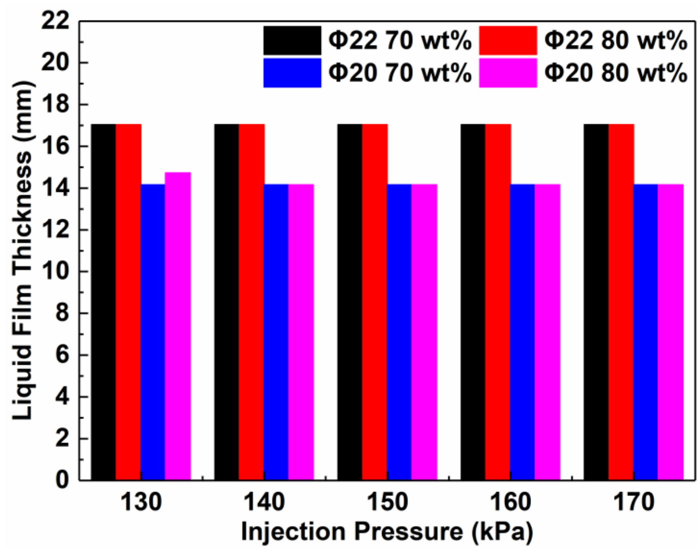

Fig. 6. Liquid film thickness *vs.* injection pressure of nozzle

A breakup length is defined as the distance from the splash nozzle outlet to the location with the first appearance of droplets, and it is one of the important indexes for evaluating the atomization performance of splash-plate nozzles (Li *et al.* 2007; Rezaei *et al.* 2019). Generally, it has been shown in practice that the shorter the breakup length, the earlier the droplets appear, and this results in a better atomization performance.

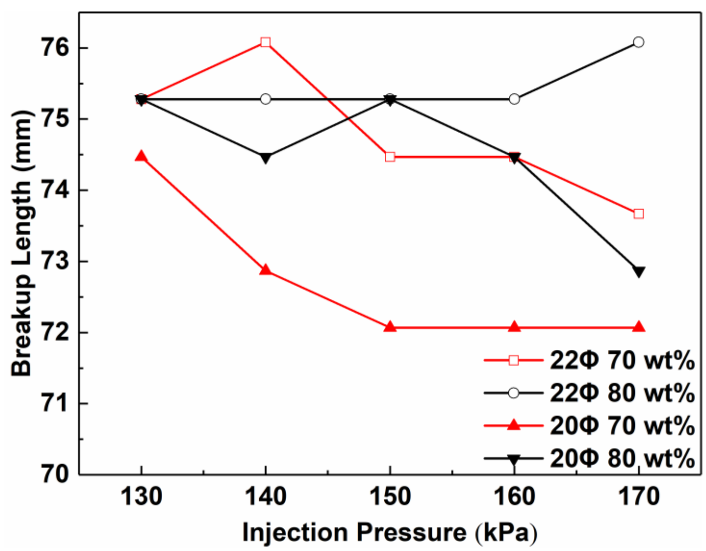

Fig. 7. Breakup length *vs.* injection pressure of nozzle

The effect of injection pressure on the breakup length was studied, and the results are shown in Fig. 7. The results demonstrated that the breakup length at the 22-mm nozzle was greater than that at the 20-mm nozzle when the BKBL with high solid content passed through the nozzle. This indicates that the effect of spray atomization is better at the nozzle with a smaller diameter under the same injection pressure. Moreover, the breakup length of BKBL with 70 wt% solid content gradually decreased at the 20-mm nozzle with the increase in the injection pressure, while it increased at first and then decreased later at the 22-mm nozzle in another simulation.

When the solid content of BKBL was 80 wt% at the 22-mm nozzle, the breakup length remained stable at first and then increased slightly under the injection pressure higher than 160 kPa. While the breakup length slightly fluctuated in the initial stage at 20-mm nozzle, and then rapidly decreased under the injection pressure greater than 150 kPa. Comparing the above results, when the solid content of BKBL increased from 70 wt% to 80 wt%, the better spray atomization effect was achieved at 20-mm nozzle under the pressure of 150 kPa, but the breakup length no longer changed later with the further increase in injection pressure.

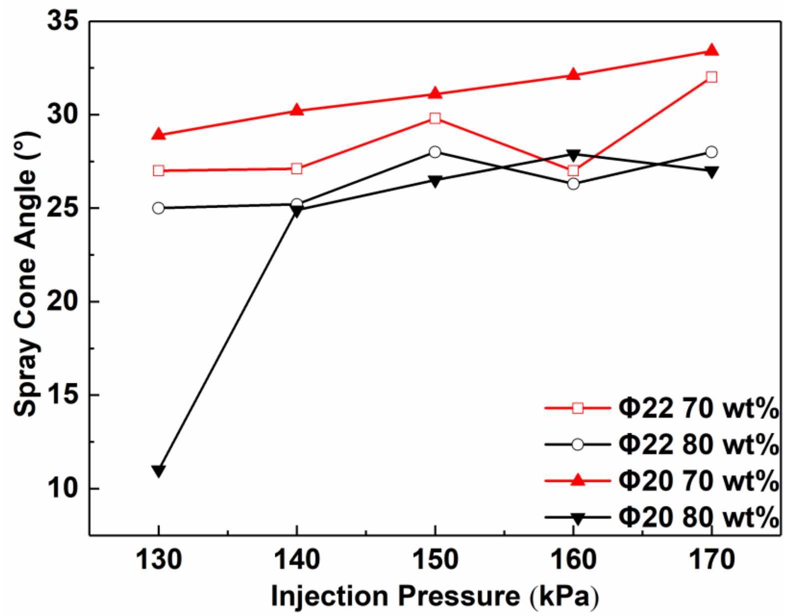

Fig. 8. Spray cone angle *vs.* injection pressure of nozzle

A spray cone angle is the angle between the outer edges of liquid film after the black liquor passes through the nozzle. Previous study indicates that the larger the spray cone angle, the wider the droplet coverage area after atomization (Rizk and Lefebvre 1985; Halder *et al.* 2004; Du *et al.* 2017). The relationship between spray cone angle and injection pressure was studied, and the results are shown in Fig. 8.

The results demonstrated that the spray cone angle at the 20-mm nozzle was clearly larger than that at the 22-mm nozzle for BKBL with 70 wt% solid content under the same injection pressure. Although the spray cone angle slightly fluctuated, the overall trend was upward with the increase in injection pressure. The changes in the spray cone angles were similar at the two nozzles for BKBL except the value at 20 mm nozzle when the solid content of BKBL was 80 wt%. This indicated that the increase in injection pressure did not have much effect on the spray cone angle. It is noteworthy that the spray cone angle at 20-mm nozzle was only approximately 11° when the solid content of BKBL was 80 wt%, which suggested that the black liquor cannot achieve a satisfactory effect of spray atomization under the injection pressure lower than 140 kPa.

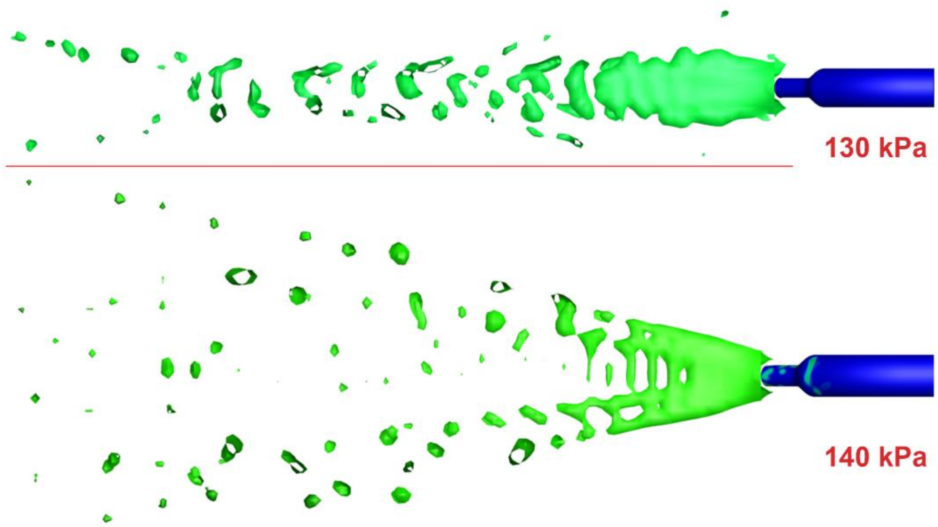

Fig. 9. Atomization of 80 wt% BKBL under 130 kPa and 140 kPa

The spray atomization was simulated under the injection pressure of 130 and 140 kPa at 20-mm nozzle when the solid content of BKBL was 80 wt%, and the results are displayed in Fig. 9. It can be seen that the BKBL left the nozzle and formed a liquid film with a relatively uniform width, which gradually developed downstream, and did not form a fan-shaped atomization area at 130 kPa pressure similar to that produced at 140 kPa pressure. This may be due to the larger viscosity of 80 wt% solid content black liquor, and the smaller injection pressure cannot make the black liquor overcome its own viscosity and achieve better atomization. Therefore, if the solid content of BKBL is increased from 70 wt% to 80 wt%, the injection pressure has to properly increase so as to meet the atomization requirement.

CONCLUSIONS

The decrease of nozzle diameter (22 mm to 20 mm) had a significant effect on the atomization parameters such as breakup length, liquid film thickness, and spray cone angle. And an increase in the injection pressure had little effect on the atomization parameters in the range of 130 to 170 kPa. The maximum pressure on the axis of the splash-plate, whatever the nozzle diameter and injection pressure, was concentrated between - 320 mm and - 310 mm. When the solid content of black liquid was increased to 80 wt%, it was necessary to select a nozzle with a diameter of 20 mm and a jet pressure of 170 kPa in order to reach the original atomization level. Therefore, if the papermaking enterprise wants to maintain the normal operation of alkali recovery furnace when increasing the amount of black liquor into the furnace, the following two points should be achieved. Firstly, small diameter nozzle should be selected and injection pressure should be further increased to improve the flow speed of black liquid flowing out of the nozzles. Secondly, the seriously corroded splash plate (stress concentration area) should be thickened to reduce the frequency of replacing splash plate and improve the operation efficiency of alkali recovery furnace.

ACKNOWLEDGMENTS

The authors would like to acknowledge the National Natural Science Foundation of China [21978161], and the Shaanxi University of Science & Technology Academic Leader Team Fund Project [2013XSD25].

REFERENCES CITED

Barreras, F., Lozano, A., Barroso, J., and Lincheta, E. (2006). “Atomization and sprays,” *Atomization and Sprays* 16(2), 127-146.

Bhargava, R., Khanam, S., Mohanty, B., and Ray, A. K. (2008). “Simulation of flat falling film evaporator system for concentration of black liquor,” *Computers & Chemical Engineering* 32(12), 3213-3223. DOI: 10.1016/j.compchemeng.2008.05.012

Cardoso, M., Avelar Costa, G. A., De Oliveira, E. D., and Ravagnani, S. P. (2012). "Simulation of eucalyptus kraft black liquor combustion in industrial recovery boilers," *Latin American Applied Research* 42(2), 197-204. DOI: 10.1099/00221287-139-8-1729

Du, W., Lou, J., Yan, Y., Bao, W., and Liu, F. (2017). “Effects of injection pressure on diesel sprays in constant injection mass condition,” *Applied Thermal Engineering* 121, 234-241. DOI: 10.1016/j.applthermaleng.2017.04.075

Foust, T. D., Hamman, K. D., and Detering, B. A. (2002). “Numerical simulation of black liquor spray characteristics,” in: *Conference Proceedings, ASME 2002 International Mechanical Engineering Congress & Exposition*, New Orleans, LA, USA, pp. 155-162. DOI: 10.1115/IMECE2002-32058

Halder, M. R., Dash, S. K., and Som, S. K. (2004). “A numerical and experimental investigation on the coefficients of discharge and the spray cone angle of a solid cone swirl nozzle,” *Experimental Thermal & Fluid Science* 28(4), 297-305. DOI: 10.1016/S0894-1777(03)00110-9

Hasanpoor, B., Javaherdeh, K., Kouhikamali, R., Salehi, M., and Mehrafzoon, M. (2011). “Numerical simulation of two phase flow in high pressure and low pressure evaporator pipes in recovery boiler,” in: 2*011 Proceedings of The 3rd Conference On Thermal Power Plants (CTPP),* Tehran, Iran.

Hou, Y., Tao, Y., Huai, X., Yu, Z., and Sun, D. (2018). “Numerical simulation of multi-nozzle spray cooling heat transfer,” *International Journal of Thermal Sciences* 125, 81-88. DOI: 10.1016/j.ijthermalsci.2017.11.011

Kim, S., Khil, T., Kim, D., and Yoon, Y. (2009). “Effect of geometric parameters on the liquid film thickness and air core formation in a swirl injector,” *Measurement Science & Technology* 20(1), Article ID 015403. DOI: 10.1088/0957-0233/20/1/015403

Lee, C. S., and Park, S. W. (2002). “An experimental and numerical study on fuel atomization characteristics of high-pressure diesel injection sprays,” *Fuel* 81(18), 2417-2423. DOI: 10.1016/S0016-2361(02)00158-8

Levesque, D., Fard, M. P., and Morrison, S. (2005). “Blspray: Understanding the effects of black liquor properties and splash-plate nozzle configuration on spray characteristics,” *Pulp and Paper Canada -Ontario-* 106(10), 34-39. DOI: 10.1007/s00107-005-0003-x

Li, G. J., and Dinh, T. N. (2004). “Aerobreakup in rarefied supersonic gas flows,” *Journal of Fluids Engineering* 126(4), 516-527. DOI: 10.1115/1.1777234

Li, S., Li, M., Zhang, S., and Wang, B. (2007). "Study on the breakup length of circular impinging jet," *Journal of University of Science & Technology Beijing, Mineral, Metallurgy, Material* 14(6), 585-588. DOI: 10.1016/s1005-8850(07)60133-9

Liu, H., Hu, H., Nairy, A., Jahan, M. S., Yang, G., and Ni, Y. H. (2013). "Viscosity of prehydrolysis liquor of a hardwood kraft-based dissolving pulp production process," *Industrial & Engineering Chemistry Research* 52(11), 3974-3979. DOI: 10.1021/ie400072c

Liu, Y. (2015). "Numerical simulation of black liquor spray characteristics and cold aerodynamic field in kraft recovery boiler," *Harbin Institute of Technology*, Harbin, Heilongjiang Province, China.

Matalkah, F., Soroushian, P., Abideen, S. U., and Peyvandi, A. (2016). "Use of non-wood biomass combustion ash in development of alkali-activated concrete," *Construction & Building Materials* 121(SEP.15), 491-500. DOI: 10.1016/j.conbuildmat.2016.06.023

Rezaei, S., Vashahi, F., Ryu, G., and Lee, J. (2019). "On the correlation of the primary breakup length with fuel temperature in pressure swirl nozzle," *Fuel* 258, Article ID 116094. DOI:10.1016/j.fuel.2019.116094

Rizk, N. K., and Lefebvre, A. H. (1980). "The influence of liquid film thickness on airblast atomization," *Journal of Engineering for Gas Turbines and Power* 102(3), 706-710. DOI: 10.1115/1.3230329

Rizk, N. K., and Lefebvre, A. H. (1985). "Drop-size distribution characteristics of spill-return atomizers," *Journal of Propulsion and Power* 1(1), 16-22. DOI: 10.2514/3.22753

Sarchami, A., Ashgriz, N., and Tran, H. (2009). "Initial perturbation amplitude of liquid sheets produced by jet-impingement nozzles," *AIAA Journal* 47(11), 2775-2779. DOI: 10.2514/1.37830

Sarchami, A., Ashgriz, N., and Tran, H. (2010). "An atomization model for splash plate nozzles," *AIChE Journal* 56(4), 849-857. DOI: 10.1002/aic.12033

Sarchami, A., and Ashgriz, N. (2011). "Splash plate atomizers," in: *Handbook of Atomization and Sprays*, N. Ashgriz (ed.), Springer, Boston, MA, USA, pp. 709-726. DOI: 10.1007/978-1-4419-7264-4_31

Schmelz, F., and Walzel, P. (2003). "Breakup of liquid droplets in accelerated gas flows," *Atomization & Sprays* 13(13), 357-372. DOI: 10.1615/AtomizSpr.v13.i4.20

Wang, L., Karimi, N., Sutardi, T., and Paul, M. C. (2019). "Combustion characteristics and pollutant emissions in transient oxy-combustion of a single biomass particle – A numerical study," *Energy & Fuels* 33(2), 1556-1569. DOI: 10.1021/acs.energyfuels.8b03602

Wang, X., and Zhao, H. (2018). "Numerical simulation of the gasoline spray with an outward-opening piezoelectric injector: A comparative study of different breakup models," SAE Technical Paper (2018-01-0272) from *WCX World Congress Experience*, Detroit, MI-US,USA, pp. 1-13. DOI: 10.4271/2018-01-0272

Xu, Y. J., Zhang, W. P., Sun, H., Zhang, D. J., and Tian, Y. (2016a). "Rheological properties and desilication during combustion of bamboo kraft black liquor," *China Pulp & Paper.* DOI: 10.11980/j.issn.0254-508X.2016.04.006

Xu, Y., Zhang, W., Sun, H., Yue, X., and Zhang, D. (2016b). "Study on the dynamic viscoelasticity of bamboo kraft black liquor," *BioResources* 11(1), 2655-2644. DOI: 10.15376/biores.11.1.2655-2644

Xu, C., Nie, W., Liu, Z., Peng, H., Yang, S., and Liu, Q. (2019). "Multi-factor numerical simulation study on spray dust suppression device in coal mining process," *Energy* 182, 544-558. DOI: 10.1016/j.energy.2019.05.201

Zaman, A. A., and Fricke, A. L. (1996). "Effect of pulping conditions and black liquor composition on Newtonian viscosity of high solids kraft black liquors," *Industrial & Engineering Chemistry Research* 35(2), 590-597. DOI: 10.1021/ie950202h

Article submitted: February 22, 2021; Peer review completed: May 8, 2021; Revised version received and accepted: June 21, 2021; Published: August 5, 2021.
DOI: 10.15376/biores.16.4.6599-6612