Disintegration of Hot Water Jet from a Pinhole Nozzle

Norihiko IKI [1] and Takumi EBARA[1]

1. National Institute of Advanced Industrial Science and Technology
   Namiki 1-2, Tsukuba, Ibaraki Pref., 305-8564 JAPAN

Small steam generator is necessary for basic experimental research of combustion in steam. Disintegration phenomena of hot water jet from the pinhole nozzle were investigated for small steam generator. SMD with the 0.04mm pinhole nozzle at room temperature is more than 3.5 times of pinhole diameter. Flash boiling atomization at 423K decreases SMD with the pinhole nozzle remarkably. Fluorine coating is effective in decrease of SMD. Most of the spray with this nozzle can evaporate by impinging on the heated wall.

1. Introduction

1.1 Background

Semi-closed gas turbine systems with oxygen burning and steam recirculation have been researched for future power station in a decade. For example, steam generators with hydrogen-oxygen combustion using rocket engine technology were proposed and developed for electric power plant [1][2]. Jericha et al. proposed several types of GRAZ cycle that can achieve higher efficiency than the other advanced combined cycles with the same turbine inlet temperature [3][4]. Miller et al. proposed Modified New Rankine Cycle (MNRC), which has a possibility to achieve 66%HHV thermal efficiency [5]. In Japan, several hydrogen combustion gas turbine systems with steam were proposed and researched as a 1700 degree centigrade class advanced combined cycle [6]. Also a methane-fueled type was researched as ACROGT2000 [7]. The characteristic feature of the both cycles is that a gas turbine and steam turbines work with common working fluid and the efficiency of the 500MW system is about 60% at HHV. In these systems combustors burn fuel with water/steam under 5MPa. But there is not enough information of combustion in steam especially under high pressure.
Therefore we have done research on combustion in steam environment. In the result of chemical kinetic simulation of burning velocity, the third body effect of steam on combustion is very important under high pressure [8]. On the other hand, instability of steam flow rate is a trouble to the accuracy of experimental data [9]. To get accurate experimental data of basic combustion properties such as burning velocity, stable supply of steam is necessary. But stability of steam supply at low flow rate was very bad than stability of the other gas such as oxygen because steam is usually generated by water bubbling in a boiler. And it is difficult to measure steam flow rates below g/s order due steam condensation due to heat loss. So we started research for steam generator.

1.2. Small Steam Generator

The concept of our steam generator is the following. The flow rate of generated steam is measured by the flow rate of supplied water. The supplied water is expected to evaporate rapidly at the same point in a steam generator because of steady generation of steam. Hence we fix the point of water evaporation by using a nozzle. We keep water in liquid phase in the upsteam of the nozzle and water evaporates in the downstream of the nozzle. Operating range of flow rate of a commercially available swirl atomizer is too large for our small steam generator. Therefore we use a metal gasket with a pinhole. This pinhole is originally designed as an orifice of tubing connector for gas flow rate control [10][11]. The droplets with this pinhole nozzle at room temperature were not small enough. Although fine spray is desirable for rapid evaporation, it is important how to supply heat of water spray evaporation in steam environment. We showed experimentally that the stable steam generation is possible by using flash boiling atomization and heating its spray on a hot wall. Atomization with pinhole nozzle was reported by Bousfield [12], Chang [13] etc. Flash boiling atomization with orifice nozzle in mm order was investigated by Lien hard [14][15], Suma [16] etc. But flash boiling with pinhole of below 0.1 mm in diameter was not clear. In this report, we examined experimental data and improved the nozzle in details. Consequently the disintegration phenomena of hot water jet from a pinhole in steam generator become clear than before.

2. Experimental Apparatus

In our small steam generator (shown in Fig.1), the purified water is supplied to the superheater through the mass flow controller from the tank pressured by Nitrogen bomb. The flow rate of the generated steam is calculated by measuring the flow rate of supplied water. Superheated water is injected from the nozzle and flash boiling atomization occurs. We expect superheated water evaporates immediately and the mass flow rate of the superheated water equals to the mass flow rate of generated steam. If the evaporation time of water is not short or mass flow rate of water is not stable, the mass flow rate of the supplied water does not represent momentarily the mass flow rate of the generated steam.

We prepared 3 pinholes of which diameters are 0.2mm, 0.1mm and 0.04mm. We investigated the flow rate of these pinhole nozzles. A 0.04mm pinhole nozzle is suitable for the

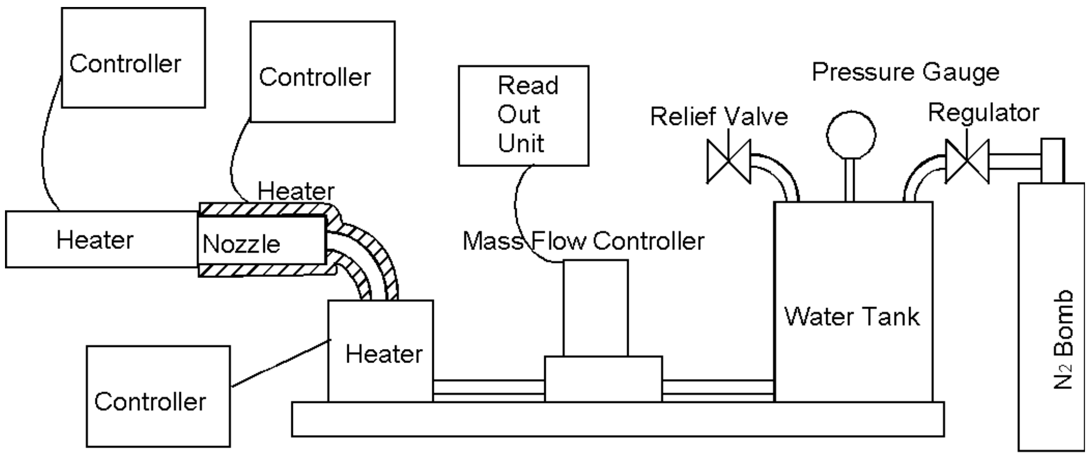


Fig. 1 Small steam generator

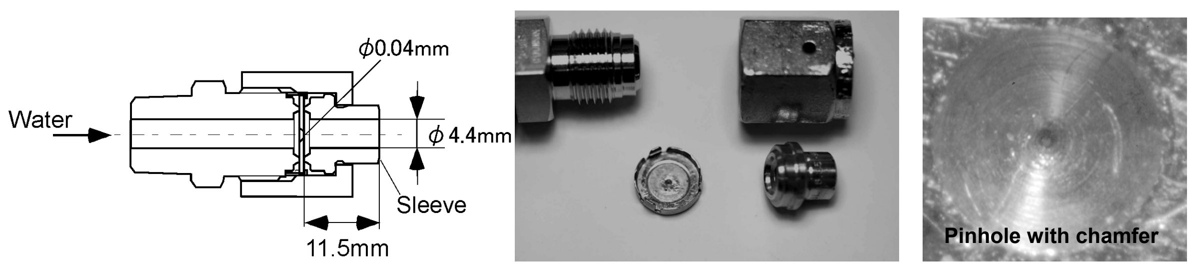


Fig. 2 Pinhole nozzle

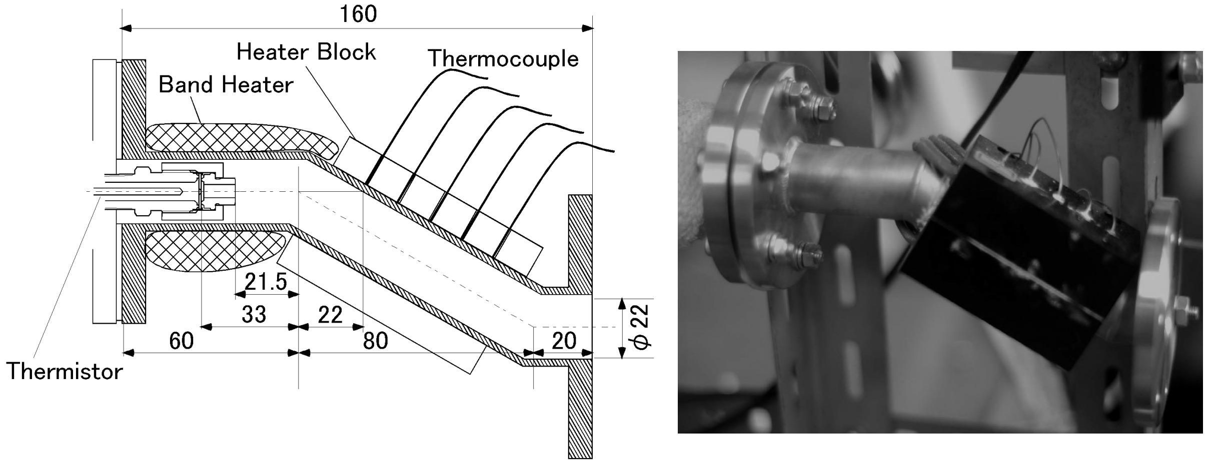


Fig. 3 Spray evaporation zone

specification of our steam generator. This pinhole nozzle is shown in Fig.2. The thickness of the pinhole plate is 0.74mm and one side of the pinhole is chamfered. The chamfer is very large comparing to pinhole diameter. The angle of the axis of nozzle and the chamfered surface is about 45 degree and length of pinhole is about 0.04mm by microscopic observation. So L/D of a 0.04mm pinhole is about 1. The chamfered side of the pinhole nozzle is set in upstream side. Temperature of water is measured by a platinum thermistor set in the nozzle and was controlled from room temperature to 473K. Injection pressure P is set from 0.1MPa to.2.2 MPa. Temperature of water is controlled from room temperature to 473K.

The sensible heat of superheated water is not large enough to provide heat of vaporization even under high-pressure. For example, pressure drop to atmospheric pressure of water at 473K at 2MPa allows only 22wt% of whole water to evaporate in steam environment. If a spray cannot be superheated enough, condensation of steam and droplet agglomeration occur and the steam flow rate becomes unstable. Hence, the only flash boiling atomization is insufficient to evaporate the whole water. It is necessary to heat the water jet in order to dry the generated wet steam rapidly. So we accelerate the spray evaporation by impinging the spray on the hot wall.

Fig. 3 shows the zone of the spray evaporation in the steam generator. The stainless steel pipe is bent in 30 degrees. Its inner diameter is 22mm and its outer diameter is 27.2mm. The heater block made of aluminum heats the pipe wall. It is difficult to define the wall temperature exactly, because surface temperature of the inner wall is not uniform. The temperature distribution pattern probably depends on spray flow rate, spray temperature, wall temperature, etc. Hence the temperature of the outer wall on the central axis of the pinhole nozzle is used as the representative temperature of the pipe wall. The wall temperature is set 373K to 473K.

Size of droplets in the spray is measured by laser diffraction method using LDSA1400A or LDSA1500A (Tohnichi computer applications co. ltd.). We use the histogram mode. The Sauter mean diameters SMD are measured at 100mm from pinhole exit. The diameters of laser beams are 14mm (LDSA1400A) and 8mm (LDSA1500A). Therefore these beams can cover path of spray from the pinhole at room temperature. But there is possibility that wide beams make precision of measurement worse.

Photographs of disintegration phenomena of the water jets are taken by digital camera (Nikon D1X) and laser sheet of YAG laser (New Wave solo 120). The thick laser sheet illuminates water jet from pinhole from side.

As the results of SMD measurement and observation of phenomena, adherence of water at pinhole exit may increase size of droplets (in Fig.4 (a)) [11]. So we prepared a pinhole plate with water-repellent processing. Thickness of the fluorine coating is in the order of several microns. We measured SMD and took pictures again. Then we observed that the spray touched slightly to the inner wall of the sleeve of the pinhole nozzle at several conditions. So we shortened the length of the sleeve from 11.5mm to 7.8mm and widened the inner diameter of the sleeve from 4.4mm to 7.2mm (in Fig.4 (b)).

3. Results

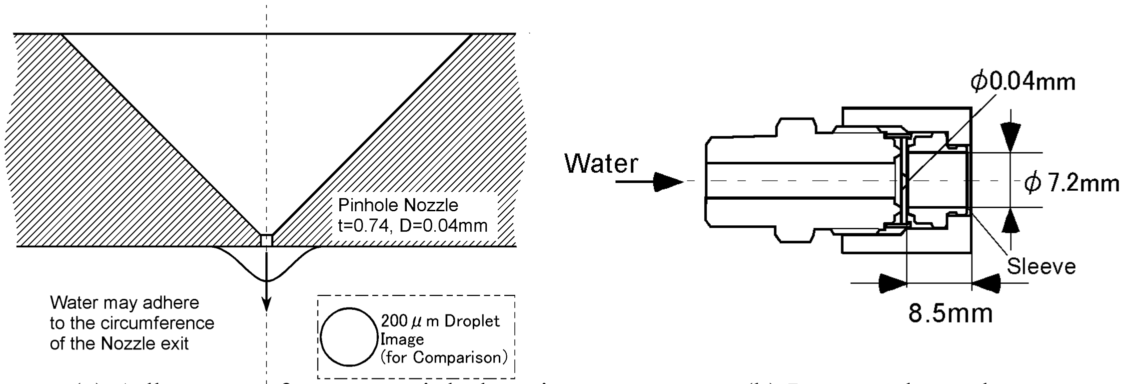
3.1. Cold Water Jet

Fig. 5 shows the flow rate of the nozzle. The flow rate is proportional to the square root of the injection pressure P. Discharge coefficient of the 0.04mm pinhole is about 0.61-0.68. Reynolds number with the 0.04mm pinhole is below 1700 at P=2.3MPa. Therefore the liquid jet from the nozzle is laminar flow and the turbulence in the liquid jet is probably negligible. Tanasawa and Toyoda [17] showed the empirical formula of critical velocity v_c from dripping to smooth jet.

$$v_c=0.65/D_n\,(\sigma/\gamma)^{3/4}\,g^{1/2} + 1.35/D_n^{1/2}\,(\sigma/\gamma)^{2/4}\,g^{1/2} - 1.09/D_n^{1/4}\,(\sigma/\gamma)^{3/8}\,g^{1/2}$$

here D_n: inner diameter of nozzle, σ: surface tension, γ: specific weight, g: acceleration of gravity

Also fig. 5 shows this critical velocity and flow rate. Since the velocities in our experiments are over v_c, water jets in this study are in the region of smooth jet. Fig. 6 shows jet number Je



(a) Adherence of water at pinhole exit (b) Improved nozzle

Fig. 4 Modification of nozzle

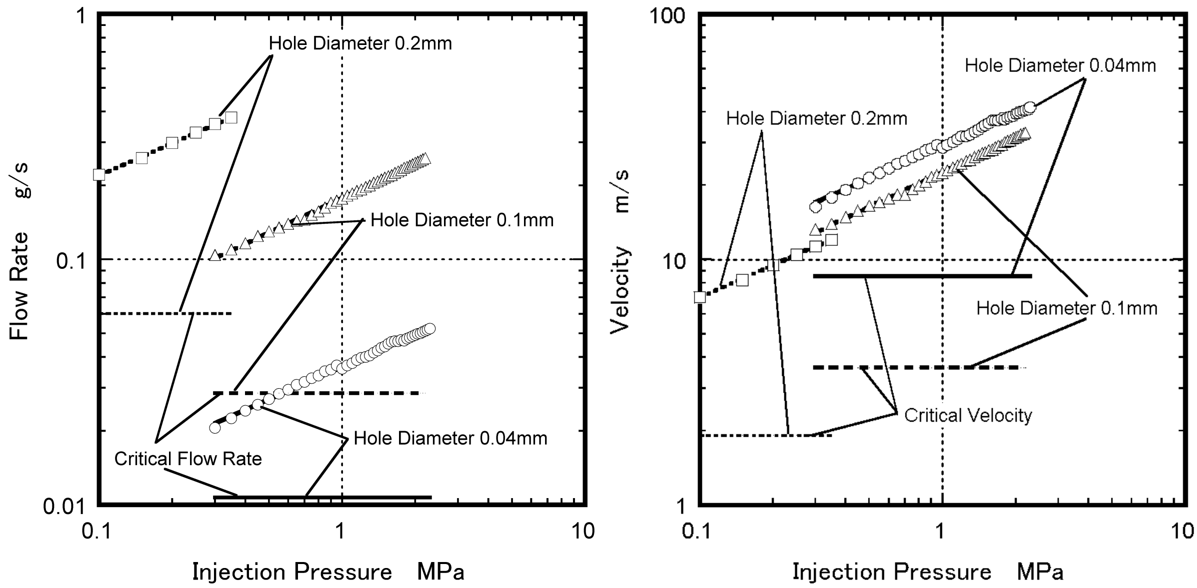


Fig. 5 Flow rate and velocity of pinhole

proposed by Tanasawa and Toyoda [18].

$$Je = \rho_l D_n v^2 / \sigma (\rho_a / \rho_l)^{0.55}$$

here ρ_l: density of liquid, ρ_a: density of air, v: velocity of liquid jet

At P>0.83MPa, Je is over 10, which is border of smooth jet and wavy jet. Je is about 10 when Re is1100 in Fig. 6. Ohnesorge number Oh of water is 0.0186 with the 0.04mm pinhole. So Reynolds number Re is about 1100 by Ohnesorge's theory when water jet transits from smooth jet to wavy jet. Also No shows that $Re = 218 (Oh)^{-0.338} (L/D_n)^{0.086}$ [19]. Since (L/D_n) of this pinhole nozzle is about 1, Re =837. Therefore, it is estimated that smooth jet changes to wavy jet when Re is from 830-1100 at P=0.5-0.8 MPa of injection pressure. Lienhard investigated breakup length BL of water jet with Reynolds when orifice diameter is 0.8-3.2mm [15]. Also Chang investigated BL with 0.1mm orifice nozzle [13]. The both experimental results show BL/D_n is roughly estimated by Weber's theory. BL/D_n of the 0.04mm pinhole nozzle is estimated as shown in Fig.6. When smooth jet change to wavy jet, it is estimated that BL/D_n becomes maximum and about 210-260 at P=0.5–0.8MPa. So the estimated BL is about 8-10mm.

Fig.7 shows disintegration of the water jet at room temperature. The water jets were illuminated by light sheet of YAG laser from left side and these photographs are reversed image. The pinhole plate with water-repellent processing was used. No liquid column is observed. The area until 8.5mm from the pinhole exit cannot be observed and breakup length BL estimated by Weber's theory is about 8-10mm. Therefore real BL may be shorter than the estimated BL by Weber's theory.

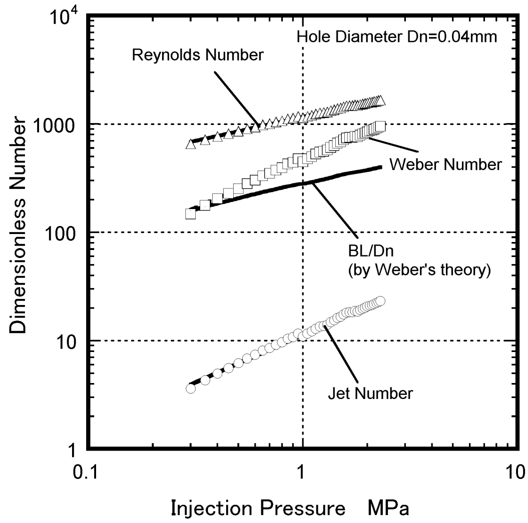


Fig. 6 Dimensionless numbers

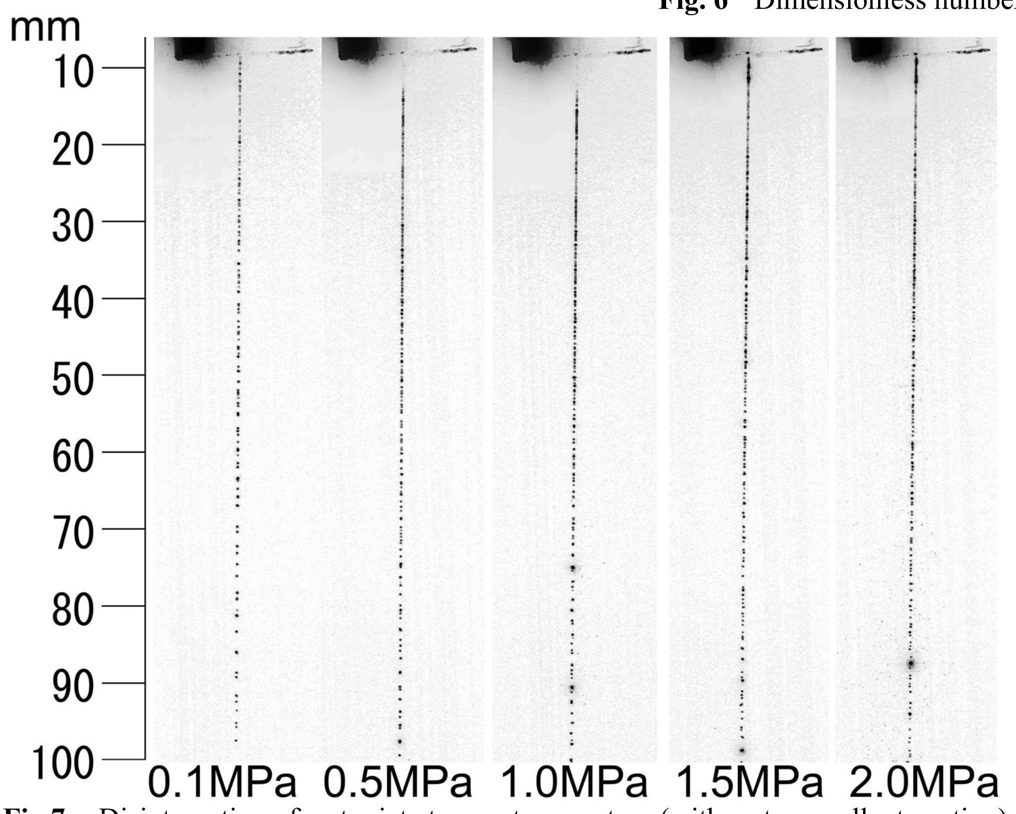


Fig.7 Disintegration of water jet at room temperature (with water repellent coating)

3.2. Hot Water Jet

Fig. 8 shows reversed images of disintegration of the hot water jet at 423K. Flash boiling atomization is observed. These images were taken with the wide and short sleeve of the nozzle. But the spray still may touch to the sleeve because some large drops are observed.

As shown in fig.9 (a) SMD at room temperature with the original pinhole decrease with increase of P. But SMD are around 200 μm at P<1.0MPa. Diameter of droplet is $1.89D_n$ by Rayleigh's theory but measured SMD are $4D_n$-$6D_n$. Since SMD are too large with comparing to the pinhole, a water drop may adhere to the edge of the nozzle exit and the liquid jet may be suppressed with the surface tension. As P increases over 2MPa, SMD decreases again. P may overcome the surface tension. At 373K SMD is smaller than that at room temperature. The adhered water drop may become smaller because water evaporates rapidly. At 423K,

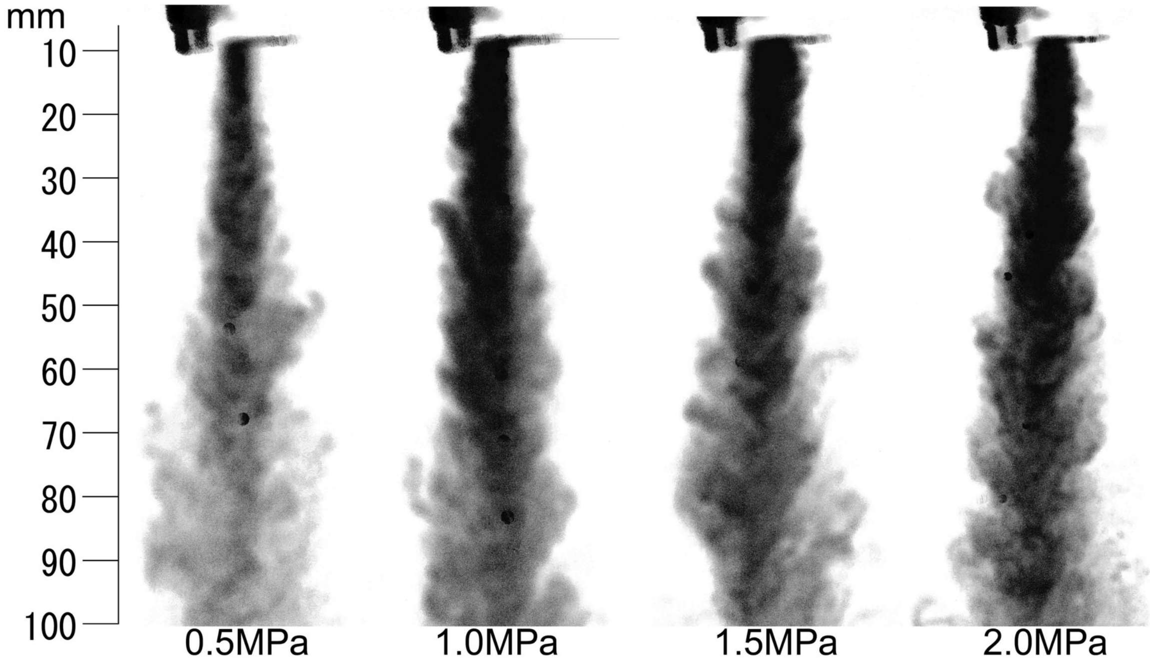
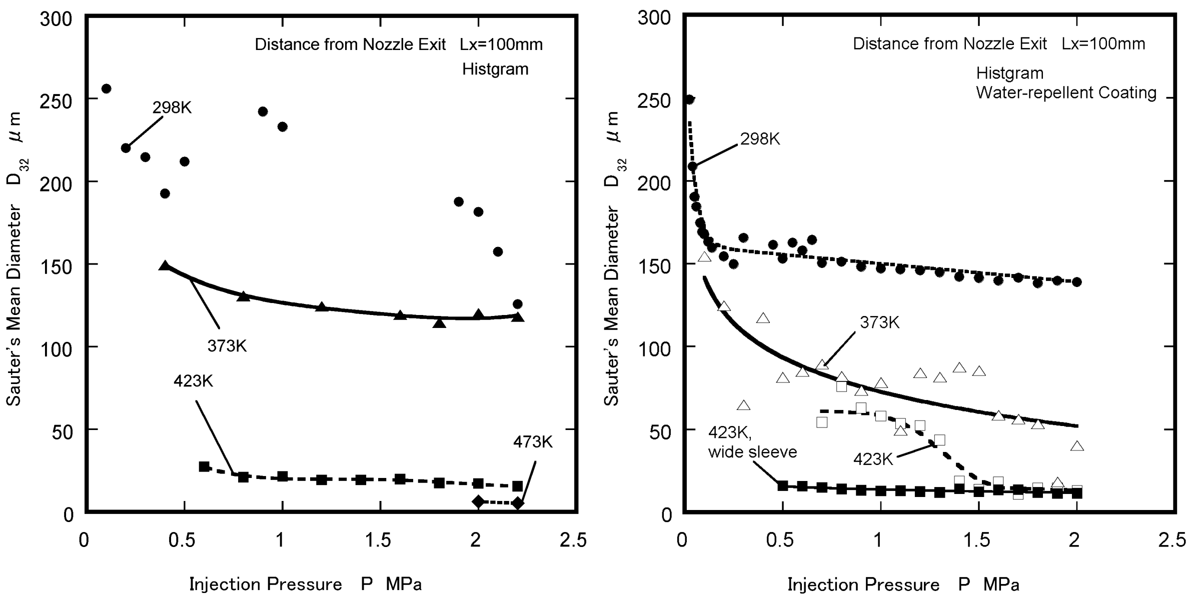


Fig. 8 Disintegration of water jet at 423K (with water-repellent coating)



(a) Pinhole without coating (b) Pinhole with water-repellent coating

Fig. 9 SMD of Pinhole Nozzle

flash boiling atomization decreases remarkably SMD to 22 μm at P=1.0MPa.

Water-repellent coating may prevent from adherence of water to pinhole exit. As shown in fig.9 (b) water-repellent coating is effective in decrease of SMD. At room temperature, SMD at P=0.1MPa and P=1.0MPa is respectively about 170 mm and about 150 mm. SMD at P>0.1MPa are $3.5D_n$-$4D_n$. So SMD are still larger than Rayleigh's theory. SMD with the pinhole nozzle with water-repellent coating is stable at room temperature even if P is below 0.1MPa. SMD at 373K and 423K are not stable because a part of spray makes liquid film on the inside wall of the sleeve of the nozzle and the liquid film sometimes disintegrates. So we measured SMD with the wide and short sleeve at 423K again. SMD are stable and about 11-16 μm.

3.3 Impingement of Spray on Hot Wall

Sensible heat of superheated water is not enough to evaporate completely. Therefore the remained spray has to be heated in the downstream of the nozzle exit. At the present work we use impingement to the hot wall to evaporate the spray completely as shown in Fig. 3.

Fig.10 shows SMD and concentration of droplets at Tw=423k under P =2MPa. At T≤413K the concentration decrease with increase of T but SMD do not vary so much. These data were took with the original pinhole nozzle. At T=423K, SMD increase remarkably. Therefore most of the spray of this nozzle can evaporate by impinging on the heated wall. The large droplets remain and increase SMD.

Fig.11 shows SMD and concentration at Tw=423K under various P. The influence of T to SMD is small at T≤398K, except P≤0.6MPa. Re-atomization on wall is dominant phenomenon. At T=423K or at P≤0.6MPa SMD and concentration are not stable because most of small droplets evaporate completely and a few large

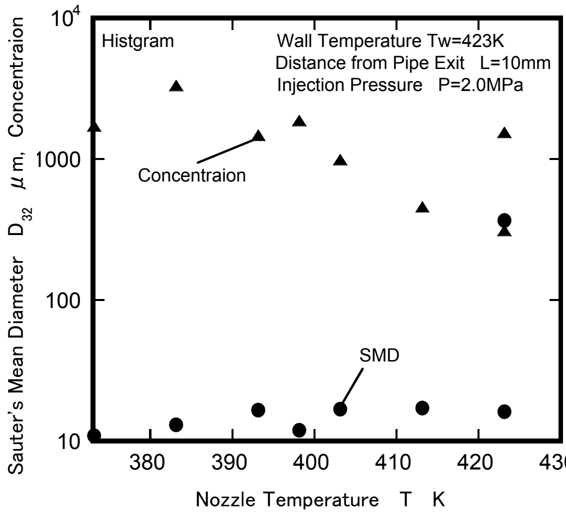


Fig. 10 SMD at Tw=423K P=2MPa

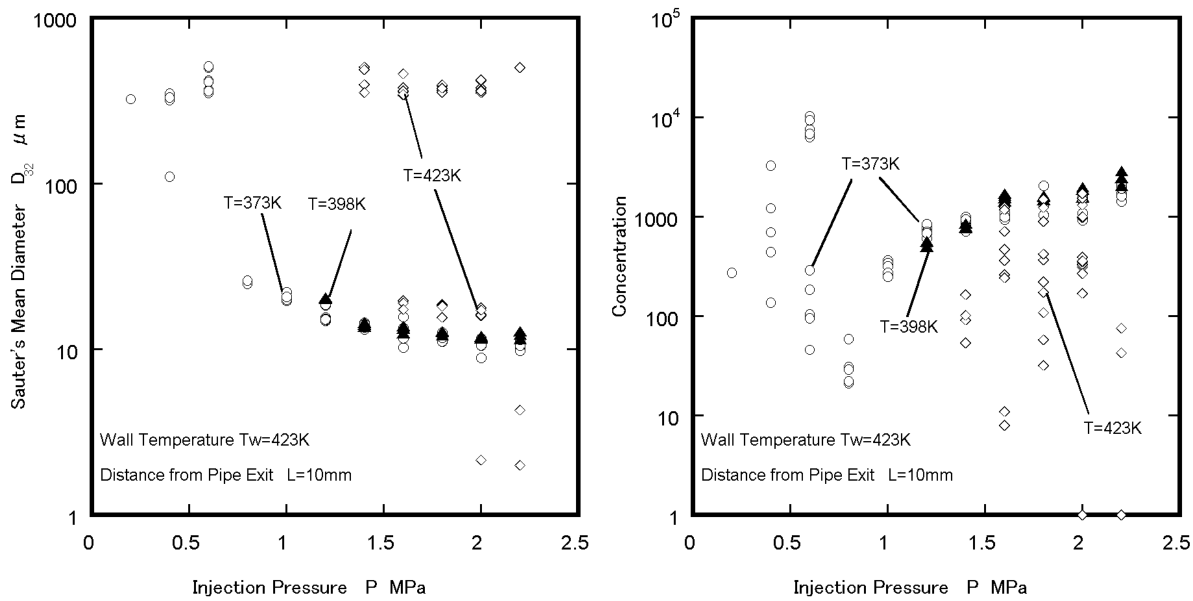


Fig. 11 SMD and concentration at Tw=423K

droplets are observed sometimes. The concentration of the spray roughly increases with P because flow rate increase with P. The concentration roughly decreases with increase of Tw due to evaporation. Therefore the influence of the evaporation delay of these large droplets to the flow rate of the generated steam is small at high Tw. When the pinhole nozzle with water-repellent coating is applied to the steam generator, SMD of impinging spray become small and the number of large droplets at the pipe exit may decrease further.
Considering the preceding phenomena, the steam generator can function at T=423K or P≤0.6MPa (at T=373K) when Tw is 423K. Sometimes the pinhole is plugged and the flow coefficient varied. To make a steam generator the countermeasures against this trouble are needed.

4. Summary

Disintegration phenomena of hot water jet from pinhole nozzle were investigated for small steam generator. SMD with the 0.04mm pinhole nozzle at room temperature is more than 3.5 times of the pinhole diameter. Flash boiling atomization at 423K decreases SMD of the pinhole nozzle remarkably. Water-repellent coating is effective in decrease of SMD. Most of the spray with this nozzle can evaporate by impinging on the heated wall.

5. References

[1] Haidn OJ, Frohlke K, Carl J and Weingartner 1996 *Proc. 11th World Hydrogen Energy Conference* **2**1418-1427
[2] Volkov AG, Bebelin IN, Gryaznov AN and Malyshenko SP 1996 *Proc.11h World Hydrogen Energy Conference* **2** 1913-1919
[3] Jericha H and Starzer O 1991 *Proc. 19th Int. Congress on Combustion Engine CIMAC* G20
[4] Jericha H and Fesharaki M 1995 *ASME paper* 95-CTP-79 1-9
[5] Miller A, Lewandowski J, Badyda K, Kiryk S, Milewski J, Hama J and Iki N 2002 *Proc. 14h World Hydrogen Energy Conference* A207e 1-12
[6] Chiba M, Arai H and Fukuda K 1996 *Proc. 11h World Hydrogen Energy Conference* **1** 13-25
[7] NEDO 1999 Annual Summary Report on Results "Advanced Carbon Dioxide Recovery System of Closed Gas Turbine Aiming At 2000K (ACRO- GT2000) ", NEDO-CO-99, NEDO, 2000
[8] Iki N, Furutani H, Hama J, Takahashi S, Kurata O and Liu F 1997 *Proc. 4th Japan-Korea Joint Sympsium 97 on Hydrogen Energy* 148-155
[9] Iki N, Furutani H, Hama J, Liu F, Takahashi S and Kurata O 1997 *J. Gas Turbine Society of Japan* **25** 97 85-92 (in Japanese)
[10] Iki N, Ebara T, Saito T and Furutani H 2002 *Proc. ILASS-Asia 2001* 321-326
[11] Iki N and Ebara T 2002 *Proc. ILASS-Asia 2002* 167-174
[12] Bousfield DW, Stockel IH and Nanivadekar CK 1990 *J. Fluid Mech.* **218** 601-617
[13] Chang JC, Shen MS and Lu JZ 2000 *Proc. ILASS-Asia '00* 85-92
[14] Lienhard JH and Stephenson JM 1966 *J. Basic Engineering: Trans. ASME* **88** 525-532
[15] Lienhard JH and Day JB 1970 *J. Basic Engineering: Trans. ASME* **92** 515-522
[16] Suma S and Koizumi M 1977 *Trans. JSME* **43** 376 4608-4621(in Japanese)
[17] Tanasawa Y and Toyoda S 1954 *Trans. JSME* **20** 92 299-306 (in Japanese)
[18] Tanasawa Y and Toyoda S 1955 *Technical Report Tohoku Univ.* **19** 135 (in Japanese)
[19] No SY 1998 *Proc. 3rd Conf. ILASS-Asia* 55-60