Heat and momentum transfer mechanisms under the direct-contact-condensation between supersonic steam flow and water jet

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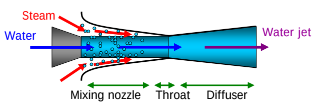
Abstract

Steam injector (SI) is a passive jet pump which operates without rotating power source or machinery and has high heat transfer performance due to the direct-contact condensation of supersonic steam flow onto subcooled water jet, and it has been expected to be applied to one of passive safety systems for the Next-generation nuclear power plants. The objective of the present study is to develop a model which is able to predict operating characteristics such as maximum discharged pressure as well as operating range of the SI. In order to achieve this, flow directional pressure distribution was measured with changing the opening ratio of back pressure valve attached at downstream of test section. Furthermore, temperature and velocity distributions in mixing nozzle were measured in order to evaluate flow structure as well as thermal hydraulic characteristics of SI. In addition, interfacial behavior of water jet was observed and quantified by calculating wave velocity with image correlation method. It was confirmed that interfacial behavior enhances heat transfer between steam flow and water jet. Existing model was applied to estimate discharge pressure at diffuser as well as to investigate operating mechanisms of SI. However that model overestimated the experimental data such as mixing temperature and discharge pressure. Unsteady two-phase flow structure including shock wave was observed at throat and diffuser, which had not been taken into account in that model. From these results, some proposal to predict operating characteristics of SI with high accuracy are presented.

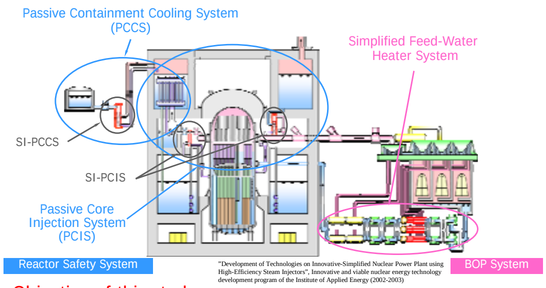
Introduction

Steam injector (SI)



- Passive jet pump driven by direct contact condensation of steam flow onto water jet.
- No need for external power supply.
- Simple and compact structure.
- High-efficiency heat exchanger.

Application of SI for Next-generation nuclear power plants



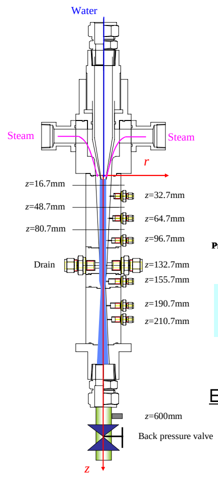
"Development of Technologies on Innovative-Simplified Nuclear Power Plant using High-Efficiency Steam Injectors", Innovative and viable nuclear energy technology development program of the Institute of Applied Energy (2002-2003)

Objective of this study

- To Clarify thermal-hydraulic mechanisms of steam injector operation for practical use.
- To develop a model which predicts operating characteristics and operating range of steam injector.

Experimental apparatus and conditions

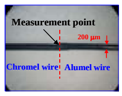
Test section



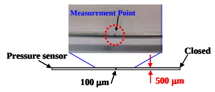
Made of polycarbonate
- Observation of flow structure.
- Supply superheat steam.

Measurement instruments

Special thermocouple



Special poitot tube



Traversed toward radial direction at 0.5 mm intervals at z=16.7, 48.7, and 80.7 mm.

Experimental conditions

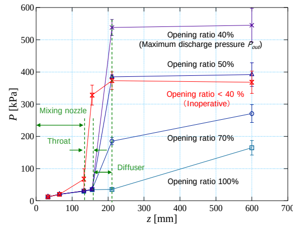
Inlet water flow rate

$M_{l,in}$:0.45~0.55 kg/s

Inlet steam pressure

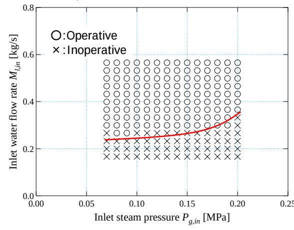
$P_{g,in}$:0.10~0.18 MPa

Operating characteristics of SI



Pressure distribution against opening ratio of back pressure valve

- It becomes to negative pressure in mixing nozzle when SI is operative.
- Discharge pressure at diffuser increases as opening ratio decreases.
- Maximum pressure exists just before inoperative point of SI. (opening ratio is 40 %)
- SI becomes inoperative with pressure increase in mixing nozzle and throat when opening ratio is over than 40 %.

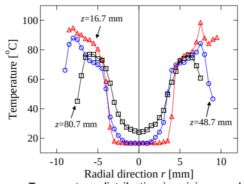


Minimum inlet water flow rate against inlet steam pressure

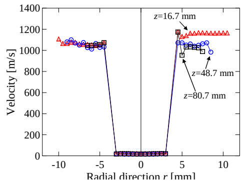
- There exists minimum inlet water flow rate for SI operation.
- Minimum inlet water flow rate increases as inlet steam pressure increases.

It is suggested that operating range of SI is limited by maximum discharge pressure and minimum inlet water flow rate.

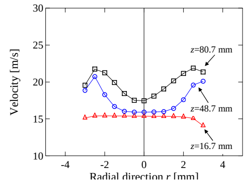
Flow structure in mixing nozzle



Temperature distribution in mixing nozzle



Velocity distribution in mixing nozzle



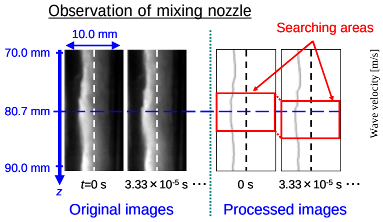
Velocity distribution in water jet

- Large temperature gaps exist between water jet and steam flow.
- Temperature increases as it goes downstream in water jet.

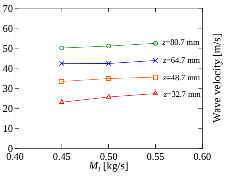
- Large velocity gaps exist between water jet and steam flow.
- Velocity distribution in water jet increases toward downstream.
- Outside of water jet seems to be accelerated.

Significant heat and momentum transfer due to direct-contact-condensation.

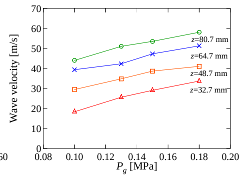
Observation of mixing nozzle



Original images Processed images



Effect of M_l on wave velocity

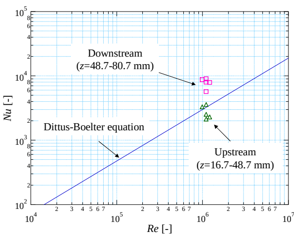


Effect of P_g on wave velocity

- Interfacial wave which propagates toward downstream is observed.
- Wave velocity is calculated by image correlation method in order to quantity the interfacial behavior.

- Wave velocity increases as it goes downstream.
- Wave velocity is significantly affected by P_g.
- Interfacial behavior seems to be correlated with momentum transfer.

Effect of interfacial behavior on heat transfer characteristics

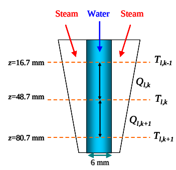


Dittus-Boelter equation

$Nu = 0.023 Re^{0.8} Pr^{0.4}$ $(10^3 < Re < 10^7)$

Turbulent forced convection heat transfer correlation equation

Calculation model of heat transfer coefficient



$$Q_l = C_{pl} M_l \Delta T_l$$
$$\Delta T_l = T_{l,k+1} - T_{l,k}$$
$$\overline{\Delta T} = (\Delta T_k - \Delta T_{k+1}) / \ln(\Delta T_k / \Delta T_{k+1})$$
$$\Delta T_k \equiv T_{g,k} - T_{l,k}$$

Heat transfer coefficient

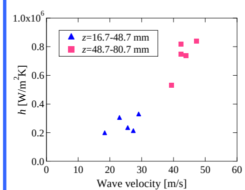
$$h = \frac{Q_l}{A_l \overline{\Delta T}}$$

Nusselt number

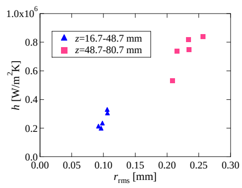
$$Nu = \frac{h \cdot D}{\kappa}$$

- Water jet is assumed as cylinder shape.
- HTC is calculated with ratio of heat quantity water jet gained and LMTD between steam flow and water jet.

h : Heat transfer coefficient [W/Km²],
Nu : Nusselt number
D : Water jet diameter [m]
k : Thermal conductivity of water [W/Km]
A_l : Water jet surface area [m²]
Q_l : Heat quantity [W]
C_{pl} : Specific heat of water [J/kgK]
M_l : Water flow rate [kg/s]
T : Temperature [°C]
ρ: Density [kg/m³]
h_{gl} : Latent heat of condensation [J/kg]
Re : Reynolds number
Pr : Prandtl number



Effect of wave velocity on HTC



Effect of interfacial fluctuation on HTC

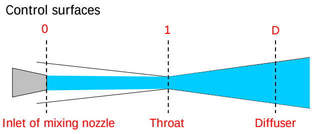
- Nusselt number at downstream exceeds Dittus-Boelter equation even though it approaches to the equation at upstream.
- HTC in mixing nozzle reaches to 0.2~0.8 MW/m²K.
- HTC increases as wave velocity and interfacial fluctuation increase.

Heat transfer in mixing nozzle is significantly enhanced by interfacial behavior.

Estimation of discharge pressure using existing model

Hypothesis of model
- Steam flow into mixing nozzle as critical flow.
- Steam flow completely condenses into water in mixing nozzle.
- Interfacial behavior of water jet is not taken into account.

Control surfaces



Index
w:water
s:steam

M : Flow rate [kg/s]
P : Pressure [Pa]
A : Cross-sectional area [m²]
T : Temperature [K]
G : Mass flux [kg/sm²]
h : Specific enthalpy [J/kg]
u : Flow velocity [m/s]
C_{pl} : Specific heat [J/kgK]
ρ : Density [kg/m³]
ζ : Pressure loss coefficient

0-1 (Mixing nozzle)

Mass conservation

$$M_{w0} + M_{s0} = M_1 = M_{w1}$$

Momentum conservation

$$P_{w0}A_{w0} + P_{s0}A_{s0} + G_{w0}A_{w0}u_{w0} + G_{so}A_{s0}u_{s0} = P_1A_1 + P_{01}(A_{w0} + A_{s0} - A_1) + G_1A_1u_1 + F_f$$

Energy conservation

$$M_{w0}h_{w0} + M_{s0}h_{s0} = M_1(h_1 + u_1^2/2) = M_{w1}(h_{w1} + u_{w1}^2/2)$$

Friction loss

$$F_f = \zeta_N(\rho_1 u_1^2/2)A_1$$

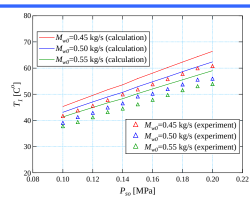
Mixing temperature

$$T_1 = (M_w h_w + M_s h_s)/(M_1 C_{p1})$$

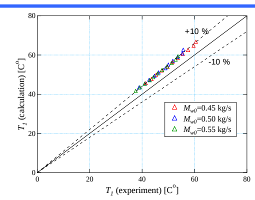
1-D (Throat and Diffuser)

Berrnoulli's principle

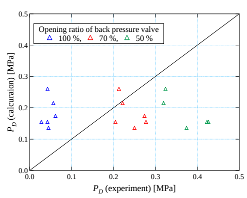
$$P_D + \rho_D u_D^2/2 = P_1 + \rho_1 u_1^2/2 - (\zeta_1 + \zeta_D)(\rho_D u_1^2/2)$$



Relation between mixing temperature T_1 and inlet condition



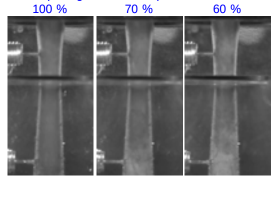
Comparison of calculated T_1 and measured T_1



Comparison of calculated P_D and measured P_D

Opening ratio of back pressure valve

100 % 70 % 60 %

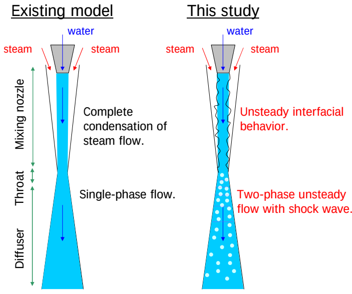


Observation of throat and diffuser

- Qualitative tendency of calculated T_1 gives close agreement with measured T_1.
- Existing model overestimates the discharge pressure P_D in all of inlet condition.
- Steam flow does not condense completely in mixing nozzle and therefore two phase flow including shock wave appears at throat and diffuser, which is not considered in existing model.

Conclusion

Existing model This study



Flow structure in SI
- Interfacial behavior enhances heat transfer between steam flow and water jet.
- Steam flow does not condense completely in mixing nozzle and it becomes unsteady two-phase flow in throat and diffuser.

Physics model for operating characteristics of SI
- Interfacial behavior in mixing nozzle and unsteady two-phase flow behavior which includes shock wave should be taken into account.
- It is highly required to develop a model which considers findings proposed in this study in order to predict operating characteristics as well as operating range of SI with high accuracy.

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