Nuclear Engineering and Design 334 (2018) 57–65

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Investigation of the supersonic steam injector operation mode

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ARTICLE INFO

Keywords:
Nuclear reactor safety
Thermal-hydraulics
Passive safety system
Two-phase flow
Direct contact condensation
Ejector

ABSTRACT

Steam injector (SI) operates as passive jet pump and heat exchanger, which is activated only by the high-pressure steam and water. SI possess simple geometry and does not require any external power supplies nor rotating machinery for the operation. It is capable of discharging subcooled water at higher pressure than the inlet, and operable as a passive jet pump. In addition, direct contact condensation heat transfer between steam and water-jet provides superior heat exchanging characteristics, more than 1,000 times that of shell and tube heat exchangers. Due to these advantageous features, SI has a great potential to be applied as a passive safety system of nuclear power plants including existing light water reactors and next generation reactors. In the present study, SI experiments targeting for the operating range and the pumping performance were carried out at 0.02–0.81 MPa inlet steam pressure and 0.21–0.80 kg/s inlet water flow rate. The SI body was manufactured by stainless steel equipped with overflow port. The water injection nozzle was designed with shaft-driving mechanism to adjust the axial location of the water jet and steam inlet area. During the experiment, SI's pump performance and operation mode were investigated by changing the inlet conditions. Maximum attainable discharge pressure and operation state of the SI were recorded at each inlet condition. In this study, liquid jet break-up length was considered to assess the SI's operation mode. Clear boundaries to explain the SI's operational range were obtained using the jet stability analysis. The research results presented here provides significant aspect to properly design operable SI as the passive safety system.

1. Introduction

Following the Fukushima-Daiichi accident, investigations on passive coolant injection systems have been given increased attention (Takeya et al., 2015; Miwa et al., 2017). In view of implementing multi-layered safety systems, steam injector (SI) can be considered as a potential passive coolant injection system which can be applied towards both existing and next-generation reactors. SI is a simply designed passive jet pump which does not require any electric power or rotating machinery for its operation. Fig. 1 depicts the schematic of the central-water jet type SI. As can be seen, it consists of (a) steam and (b) water nozzles, (c) converging mixing nozzle, (d) throat section, and (e) diffuser, respectively. Within the convergent condensing section, called mixing nozzle, driving fluid is accelerated due to the channel geometry as well as the interfacial momentum transfer between steam and water phase. It is capable of discharging the condensed fluid at least two times the inlet fluid pressure. Moreover, due to SI's superior heat transfer capability, about 1000 times higher heat transfer coefficient than the shell-tube type heat exchanger can be achieved. SI can be utilized in various engineering applications including boiler, locomotive engine parts, refrigeration system, feedwater pumps, direct condensers, and ejectors for steam-water systems and so on (Trela et al., 2009; Yan et al., 2005; Smierciew et al., 2015). For the nuclear reactors, possible applications include feedwater system for Isolation Condenser (IC), Passive Core Cooling System (PCCS), and even Steam Generators (SG), using the steam from RPV or SG as a primary working fluid (Narabayashi et al., 2000; Abe and Shibayama, 2014; Cattadori et al., 1995; Dumaz et al., 2005; Takeya et al., 2015; Miwa et al., 2016).

Depending on the types of SI, the driving fluid can be either the steam or the water jet. However, from the recent SI researches, experiments with central-water jet type SI have been carried out widely due to its stable start-up and reliable operation. As the central water jet and the steam are in contact at the mixing nozzle section, two fluids begin to go through direct contact condensation. During the direct contact condensation process, negative pressure is attained within the mixing nozzle section and operating fluids are passively drawn into the SI. This operation can be sustained without the use of any external electric power source, which is one of the advantageous features of SI

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https://doi.org/10.1016/j.nucengdes.2018.05.002
Received 4 January 2018; Received in revised form 6 April 2018; Accepted 2 May 2018

Nomenclature

D_{jet}	liquid jet diameter [m]
H	enthalpy [J/kg]
L_{break}	dimensionless jet breakup length [–]
L_{max}	dimensionless maximum jet length [–]
JLR	jet length ratio [-]
L_{mix}	length of the mixing nozzle [m]
m_s	steam mass flow rate [kg/s]
m_w	water mass flow rate [kg/s]
M_R	momentum ratio [–]
p	water nozzle pull-out length [m]
P	pressure [Pa]
q''	heat flux [W/m^2]
R	gas constant [J/K-mol]
T	temperature [°C]
U_R	velocity ratio [–]
V_{s0}	steam velocity at steam nozzle inlet [m/s]
V_{w0}	water velocity at water nozzle exit [m/s]
Z_{break}	jet breakup length [m]

Greek symbols

Λ_{jet}	jet length ratio [–]
ρ	density [kg/m^3]
ω	mass flow ratio [–]

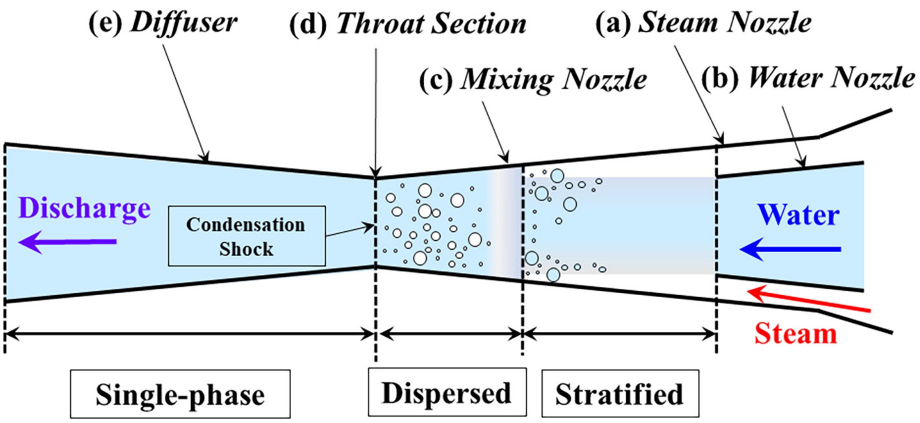

Fig. 1. Schematic of the SI Operating Mechanisms.

systems as a passive steam condenser/pump for various industrial applications including the reactor coolant system for the nuclear power plant.

Notable experimental works performed on the central-water jet type SI is tabulated in Table 1. Notice that the database for the larger steam inlet pressure exceeding 0.5 MPa hasn't been investigated well enough to this date. Also, from a recent study of the SI, it is known that the installation of the overflow port enhances SI's stability by efficiently ejecting the non-condensable gas from the system during the start-up (Takeya et al., 2015). Additionally, it is also reported in the review article by Takeya et al. (2015) that the installation of the throat-tube in between mixing nozzle and diffuser does not significantly improve the SI performance. However, it was shown in our previous experiment that the operative and inoperative inlet conditions still exist for the central-water jet type SI even with the overflow port installation (Miwa et al., 2016). Other notable SI experiments include the investigation of thermal-hydraulic characteristics, CFD calculations, turbulent behavior of the water jet, and so on (Fukuichi et al., 2009; Shimizu et al., 2008; Shah et al., 2014; Narabayashi et al., 1997). Further experimental investigations are necessary to confirm the operation criteria of the SI system with extended experimental database.

As two-phase mixture flows through a mixing nozzle, due to the direct contact condensation process between steam and water jets, local pressure rapidly increases at the throat section. As depicted in Fig. 1, stratified two-phase flow regime with abrupt steam-water interface is attained in the mixing nozzle, which has been observed by the authors who conducted the visualization studies (Abe and Shibayama, 2014; Kwidzinski 2015). Also, flow regime transition occurs from stratified two-phase flow to dispersed two-phase flow during the direct contact condensation process (Grolmes). The supplied steam is eventually condensed into a subcooled single-phase flow at the diffuser section in ideal operation conditions. In the actual scenario, non-condensed bubbles exist in diffuser section, thus, condensed fluid exits from SI as a dispersed flow regime. The location for achieving a complete

Table 1
Available Experimental Data on Central Water Jet.

Researchers	SI-Type	Geometric Features	Inlet Conditions
Grolmes (1968)	Central-Water Jet	Downward; No Overflow; With Throat-tube	P_{s0} = 0.0–0.36 MPa M_s = 0.018–0.082 kg/s P_{w0} = 0.0–0.57 MPa M_w = 0.45–1.36 kg/s
Miyazaki et al. (1973)	Central-Water Jet	Downward; No Overflow; No Throat-tube	P_{s0} = 0.067–0.55 MPa M_s = 0.009–0.048 kg/s P_{w0} = 0.11–0.4 MPa M_w = 0.22–0.58kg/s T_{w0} = 8.5–59 °C
Narabayashi et al. (1996)	Central-Water Jet	Downward; With Overflow; No Throat-Tube	P_{s0} = 0.13–0.15MPa P_{w0} = 0.17 MPa T_{w0} = 14.3 °C
Deberne et al. (1999)	Central-Water Jet	Horizontal; No Overflow; No Throat-Tube	P_{s0} = 0.4–0.8 MPa P_{w0} = 0.11–0.32 MPa T_{w0} = 15–40 °C
Li et al. (2010)	Central-Water Jet	Horizontal; No Overflow; No Throat-Tube; Swirling Vane	P_{s0} = 0.05–0.25 MPa P_{w0} = 0.4–1.0 MPa T_{w0} = 18–70 °C
Shibayama et al. (2010)	Central-Water Jet	Downward; With Overflow; No Throat-Tube	P_{s0} = 0.1–0.18 MPa M_w = 0.45–0.55 kg/s
Zhang et al. (2012)	Central-Water Jet	Horizontal; No Overflow; With Throat-Tube	P_{s0} = 0.02–0.1 MPa P_{w0} = 0.1–1.0 MPa T_{w0} = 25–70 °C
Abe et al. (2014)	Central-Water Jet	Downward; With Overflow; No Throat-Tube	P_{s0} = 0.07–0.20 MPa M_w = 0.45–0.55 kg/s T_{w0} = 19.6 ± 0.5 °C
Miwa et al. (2016)	Central-Water Jet	Horizontal; With Overflow; No Throat-Tube	P_{s0} = 0.18–0.63 Mpa M_w = 0.38–0.80 kg/s T_{w0} = 22.0 °C