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Experimental investigation of condensation wave structure in steam–water injector

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ABSTRACT

The paper presents the results of experimental investigation of supercritical two-phase flow in steam–water injector. In the region of condensation shock wave, flow structures were captured with high-speed video camera simultaneously with recordings of pressure and temperature distributions. Visualisation of condensation terminus showed formation and evolution of vapour clouds. Their disappearance was accompanied by pressure pulses, which were recorded on the channel wall. In addition, dynamics of flow instability caused by excessive backpressure at the injector outlet was examined.

1. Introduction

Steam–water injector is used in industrial applications since XIX century, originally for feeding water into boilers, especially of steam engines. The most important advantage of the steam injector is its potential reliability due to lack of moving parts and ability to work without electric power supply. Steam injector is also a relatively small device. The interest in steam injectors revived with new applications to safety systems of nuclear power plants [1,2]. Other applications were also proposed for the chemical industry [3], refrigeration [4], desalination [5], petroleum engineering [6], district heating [7], supercritical Rankine cycles [8,9] etc.

Schematic view of the supercritical steam injector (SI) considered in this work is shown in Fig. 1. It consists of four main parts: converging–diverging steam nozzle (SN), water nozzle (WN), mixing chamber (MC) and diffuser (DF). The steam nozzle is arranged centrally and its exit is encircled by water nozzle outlet. Superheated steam, the motive medium, enters the SN at small velocity. In the nozzle, the steam is expanded and accelerated to a supercritical (supersonic) velocity. Inflowing the MC, the steam creates a low static pressure, which causes the water to be drawn in through the WN annular outlet. In the MC, the steam transfers its momentum and heat to the water. Resulting condensing two-phase flow remains at almost constant pressure in the convergent MC. When the vapour–water mixture enters the MC throat, it is compressed in a shock wave where vapour phase completely condenses. Further compression takes place in the DF and only liquid water leaves the injector. Two-phase flow in the mixing chamber is supercritical with respect to its velocity. The term supercritical is used to reflect the fact that critical (sonic) velocity in two-phase mixture depends on a frequency of the pressure perturbations propagating in such medium [10–12].

The flow of steam and water in the mixing chamber and in the shock wave region is very complex and different flow patterns appear there [13]. Annular flow starts at the mixing chamber inlet. Further downstream, due to the entertainment process, droplets appear in the flow core. Then, as the vapour condensation progresses, liquid phase starts to prevail with the vapour becoming dispersed phase in the form of bubbles or larger foam-like structures present in the shock wave region.

Due to complex nature of heat, mass and momentum transfer processes present in the mixing chamber, design and modelling of steam injectors is still a challenge. The accompanying two-phase flow structures depend on the mutual configuration of steam and water nozzles. The studies of thermal and flow characteristics of injector with central steam nozzle can be found e.g. in [1,2,7,14,15] while the injector with central water nozzle arrangement was investigated in [16–19]. In these works, pressure and temperature profiles along the injector were measured. In [13,15,16], the distributions of pressure, temperature and velocity in cross-section of the mixing chamber are also reported while [2,15,16] give the results of void fraction measurements. These experimental results were used to close or validate mathematical models, 0D for injector exit pressure [1,17,20] or 1D for axial

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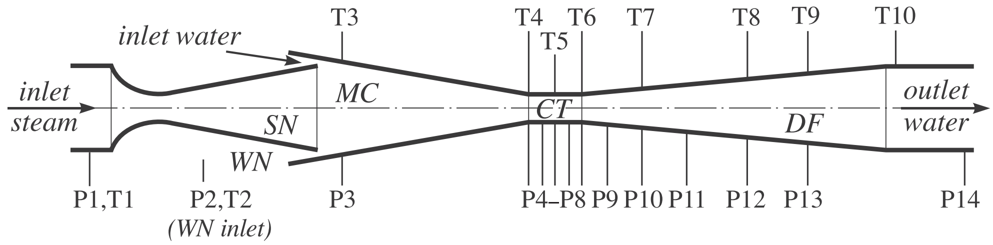

Fig. 1. Sketch of supercritical steam–water injector: *SN* – steam nozzle, *WN* – water nozzle, *MC* – mixing chamber, *CT* – cylindrical throat, *DF* – diffuser, P1–P14 – pressure measurement points, T1–T10 – thermocouple locations.

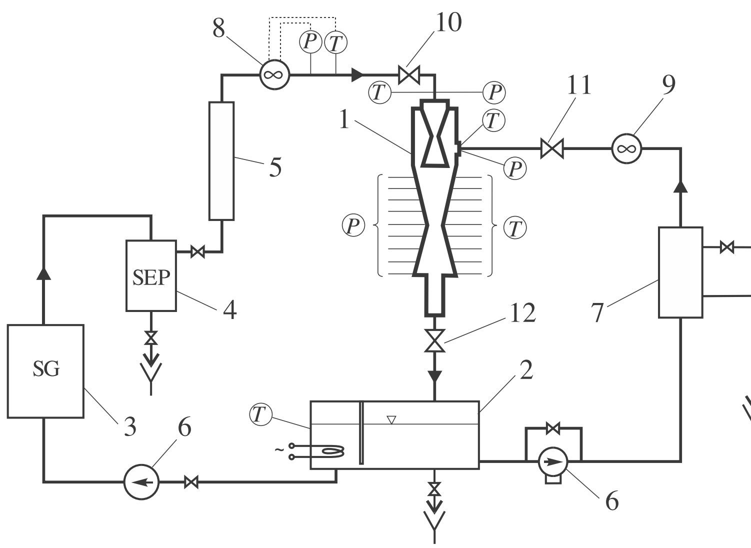

Fig. 2. Schematic diagram of experimental setup: 1 – steam–water injector, 2 – water container with degasifier, 3 – steam generator, 4 – steam separator, 5 – steam superheater, 6 – pump, 7 – cooler, 8 – steam flow meter, 9 – water flow meter, 10 – steam flow control valve, 11 – water flow control valve, 12 – backpressure control valve.

Table 1
Principal dimensions of the investigated steam–water injector.

Dimension	Value [mm]
Steam nozzle	
Throat diameter	8.5
Outlet diameter	17.0
Water nozzle	
Inner diameter	18.0
Gap	1.0
Mixing chamber	
Inlet diameter	20.0
Throat diameter	10.1
Length of conical section	100.0
Length of cylindrical throat	18.0
Diffuser	
Outlet diameter	30.0
Length	211.0

distributions of flow parameters [2,21,22]. More detailed 2D and 3D CFD simulations of the injector flow were also done and could be found in [14,18,23]. A recent and comprehensive review of steam injector models and experiments is presented in [24]. It should be noted that steam–water injector should be distinguished from water–steam one (i.e. injector with central water nozzle and liquid as a motive stream). The flow structure in these two types is entirely different, although average pressure and temperature profiles along the mixing chambers and diffusers are similar [8,25,16,17]. In addition, the condensation process in the mixing chamber of steam–water injector is similar to direct contact condensation (DCC) of a steam plume in a water pool [27,34], except for the strong pressure wave which appears in the injector only.

This paper presents the results of experimental investigation of the two-phase flow in steam–water injector with particular attention paid to the region of the condensation shock wave. Measurements of pressure and temperature along the mixing chamber and diffuser walls were acquired together with synchronized video recordings to reveal the flow dynamics and structures associated with the final stages of condensation. It is anticipated that the presented experimental results will provide data to validate numerical simulations of condensing flow in the steam–water injector. Due to large velocity slip between phases and complexity of interfacial heat and mass transfer processes such simulations are challenging. Recently, interesting results were reported in [14,23]. However, the characteristic pressure wave in the MC throat was not reproduced there.

2. Experimental setup

Flow characteristics of the supercritical steam–water injector were investigated at the Szewalski Institute of Fluid-Flow Machinery on a purpose-built experimental stand. The experimental setup scheme is shown in Fig. 2. The steam (motive fluid) is fed to the injector 1 from the boiler 3 through a separator 4 and superheater 5. The water is not sucked into mixing chamber as in real SI working conditions but is pumped (6) for better control of the flow rate.