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# Experimental Study of Steam–Water Direct Contact Condensation in a Horizontal Pipe Geometry †

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**Abstract:** The phenomenon of direct contact condensation (DCC) has an advantageous feature of high heat, mass, and momentum transfer efficiencies and hence is highly significant for various steam-related industries such as chemical and nuclear industries. The present work investigates the underlying physics of steam plume shapes during steam–water DCC of saturated steam injection into a subcooled water-filled restricted geometry. These experiments have been performed using an orifice-type nozzle for saturated steam injection into a circular, horizontal pipe. To study the effects of pressure and the degree of subcooling of water on the steam plumes, the performed study utilized initial steam pressure and water temperature in the ranges of 1–2 bars and 60–70 °C, respectively. Numerous plume shapes such as conical, elliptical, and divergent are observed under different experimental conditions, which elongate and extend at higher subcooling temperatures. The temperature distribution within the test section as a result of steam injection has also been studied. The condensation-induced water hammer (CIWH) has also been observed under various conditions in terms of a propagating pressure oscillation.

**Keywords:** multiphase flow; direct contact condensation; plume shape; thermal hydraulics

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## 1. Introduction

DCC is a complex and significant two-phase phenomenon that finds applications in many industrial setups such as steam de-superheating systems, condensate recovery systems, and steam-jet pumps, and it is quite important in applications such as district heating systems (DHSs) for domestic heating requirements and in emergency core cooling systems (ECCSs) of nuclear power plants.

In the past few decades, researchers have studied different aspects of this subject and mainly worked on the assessment of steam plume geometry, evaluation of average DCC heat transfer coefficient, and estimation of condensation regime maps [1]. Many numerical [2,3] and experimental [4,5] studies have been performed, until recently, on steam injection into quiescent water 'pools'. In case of 'restricted geometries', the previous studies were based upon the injection of steam into water to demonstrate the different condensation regimes and modes [6]. Unlike past studies, Datta [7] attempted to study different parameters of subcooled water being injected into a horizontal pipe filled with steam, but he did not study the injection of steam into a geometry having subcooled water.

Several experimental facilities such as PMK-2 at the Hungarian Atomic Energy Institute [8,9] have been established to study the pressure transients during steam–water DCC, i.e., condensation-induced water hammers (CIWHs). A CIWH is a precursor to stratified-to-slug flow transition along with increased flow instability making the condensation physics more complicated.

In this study, a circular, horizontal pipe is selected for the investigation of DCC steam plume shapes, and steam is injected via a single-hole, orifice-type nozzle into the subcooled water. A deep understanding of steam plume shapes, temperature, and pressure distribution is crucial for technological advancement in the safe design and operation procedures of nuclear and other steam-related industries.

## 2. Materials and Methods

The experimental facility setup at PIEAS is shown schematically in Figure 1. The parameters shown in Table 1 are selected because they are the most commonly occurring conditions in the steam condensate recovery systems wherein steam is present at relatively higher temperatures (60–70 °C) and lower pressures (1–2 bar). The setup majorly comprises an electric boiler with a surge tank, a circular Perspex pipe (main test section), an orifice-type nozzle, temperature and pressure instrumentation, and steam medium piping. The transparent Perspex pipe (72 inch long and $2\frac{1}{4}$ inch OD; L/D~36) resembles Datta's [7] test section (stainless steel pipe having L/D~30) and has K-type thermocouples (M8, probe length = 1 inch, ~0.5 K accuracy) and four pressure transmitters (0.2% FS accuracy) installed on it; all instruments were duly calibrated, captured by high-speed camera, and recorded by a DAQ system (Pangu Automation System Co., Ltd., VX8124R, Hangzhou, China). The saturated steam was injected horizontally as a stable sonic jet in the Perspex pipe via a nozzle. Steam plume shapes were captured for horizontal steam injection against a water degree of subcooling at different steam injection pressures.

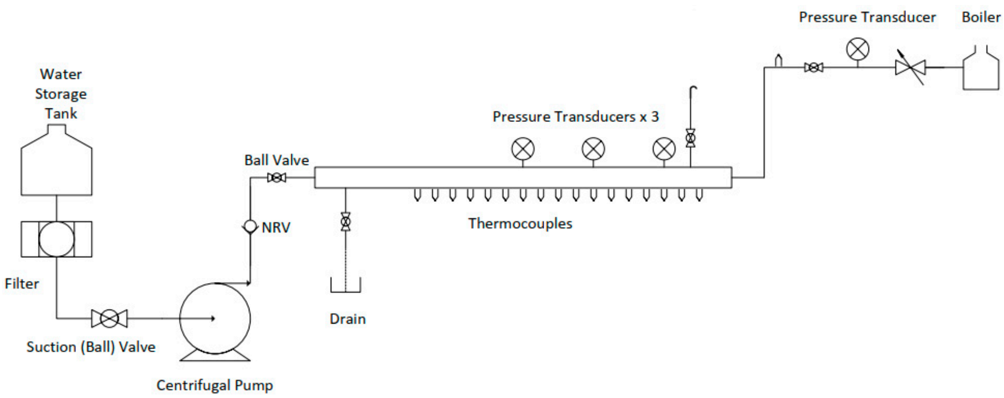


**Figure 1.** Schematic representation of DCC setup.

**Table 1.** Particulars of Operating Conditions.

| Parameters | Values |
|---|---|
| Steam Injection Pressure | 1–2 bar |
| Water Temperature (Degree of Subcooling) | 60–70 °C |
| Inlet Diameter of Nozzle | $\frac{1}{2}$ inch |
| Exit Diameter of Nozzle | 3 mm |

## 3. Results and Discussion

Different steam plume shapes obtained are captured through a high-speed camera because the system is highly turbulent and changes the water subcooling degree in a matter of milliseconds. Elongated steam plumes are obtained for lesser degrees of subcooling, i.e., at elevated water temperatures, quite possibly due to decreased condensation capacity at higher temperatures. At lower to intermediate pressures, the plume becomes inclined at an angle and ultimately stabilizes itself at relatively higher pressure values and increased water temperatures. Three major types of steam plumes have been observed: conical, elliptical, and divergent, as shown in Figure 2. The formation of conical plumes can be attributed to higher degrees of subcooling or condensation potential at lower pressure values immediately at the start of steam injection. However, the conical plumes are converted into elliptical and divergent at increasing pressure values and water temperature as a consequence of decreasing condensation potential. There is an observable temperature distribution along the pipe length following the steam injection, as shown in Figure 2, which shows the readings of thermocouples installed along the length of pipe during steam injection, at the instant when steam plumes are captured; i.e., the ambient water temperature rises as steam is added, thereby changing the degree the subcooling of water. In other words, Figure 3 indicates steam-front propagation within the test section.

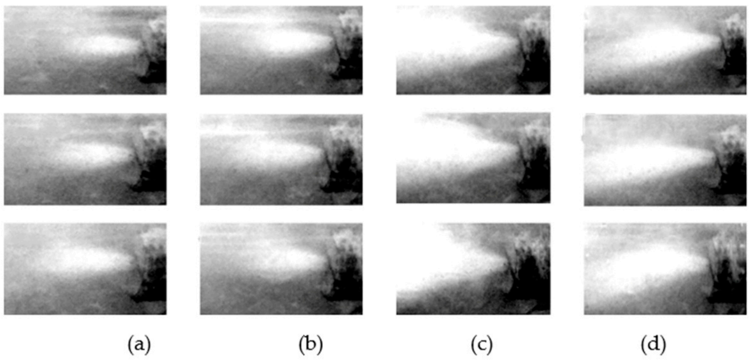


**Figure 2.** Variations in steam plumes with increasing water temperature (plume elongation) at 1.5 bar: (**a**) conical plumes; (**b**) elliptical plumes; (**c**) divergent plumes; (**d**) plumes with an inclination angle.

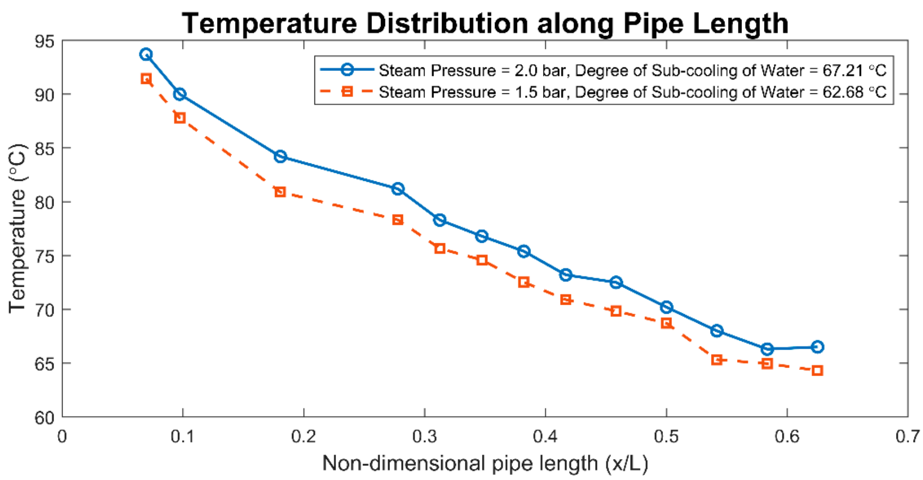


**Figure 3.** Temperature distribution along pipe length for two operating conditions.

In terms of validation of our setup and results, the temperature distribution obtained in the DCC-1 experiment (at 2 bar steam pressure and water temperature of 29.97 °C) of Datta et al. [7] is nearly similar to our data (at 2 bar steam pressure, water temperature of 32.79 °C). Similarly, no prior experimental work is available to validate the plume study for horizontal geometries. Considering the novelty of this field, some computational studies slightly confirm our estimated plume shapes: a recent work [10] utilized CFD simulation in a vertical pipe under stable sonic jet conditions and reached conclusions, i.e., elongation of plumes with injection pressure, transition of conical plumes with increasing pressures, etc., that conform to our findings.

## 4. Conclusions

In this experimental investigation, different steam plume shapes have been observed for saturated steam injected into subcooled water in a circular, horizontal geometry. The dependence of steam plume shapes on the steam injection pressure and degree of subcooling of water medium has been studied in a circular pipe. Some of the significant conclusions from the experimental study can be outlined as follows:

- Under these experimental conditions, three different steam plumes have been identified, i.e., conical, elliptical, and divergent.
- The temperature distributions obtained for two different steam pressure and water temperature values show decreasing trends along pipe length in a similar fashion.
- The steam ejected from the nozzle can be deflected downwards (or upwards) at an inclination from the reference nozzle axis due to high turbulence and CIWH occurring.
- Steam plumes elongate and extend as the temperature of subcooled water increases.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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