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CONDENSATION IMPLOSION EVENT IN STRATIFIED WATER-STEAM SYSTEM

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Abstract

The paper presents experimental data obtained from second MOD2 Pulser Test Facility version. The unique aspect of the current series of experiments is that they have shown a possibility to induce condensation implosion events in a horizontal cylindrical pulser (pre-filed by saturated steam) solely by varying the introduction rate of sub-cooled water. Interface disruption is triggered when an increasing liquid-vapor inter-face generates a growing condensation rate that leads to larger vapor flows. Vapor flow and condensation induced shear initiate surface waves and when these exceed a critical growth rate complete interface disruption leading to a rapid condensation pulse. The dependence of this critical liquid flow rate on system pressure and geometry of liquid supply nozzles has been explored. Four distinct condensation modes have been identified.

KEYWORDS

Condensation, implosion, phase change

INTRODUCTION

Two-phase fluid states can depart from thermal equilibrium to various degrees. An example of a two-phase state that can be far from equilibrium is horizontally stratified flow of steam over sub-cooled water. Such states are characterized by an extremely wide range of inter-phase mass, energy and momentum transfer rates. Under certain conditions a positive feedback between the condensation rate and the area of the inter-phase surface can be present. That is, condensation induced shear alters the inter-phase surface area, this in turn affects the mass and momentum transfer rate and thus the shear on the inter-phase surfaces. For some states the feedback can become so strong that an exponentially increasing condensation rate is initiated. The inter-phase surface will then be shattered and the rate of condensation becomes so high that it exceeds the inertial time constants of steam. The local pressure then drops down to the saturation pressure of the liquid and the resulting pressure differences within the system can lead to significant fluid motion in an inverse direction to the classical natural circulation. The generated inertial forces will strongly perturb the entire thermal hydraulic system and under certain circumstances can lead to damage. For this reason in the past this sequence of phenomena has been identified as “condensation shock” or “condensation water hammer” and most studies in this area have been directed at its prevention [1-4].

In other hand, positive aspect of this phenomenon could be that during condensation implosion event the local pressure drops suddenly and markedly. Pressure gradient created between different parts in the thermo-dynamic system could be employed to perform certain tasks. If appropriate cycle parameters will be chosen, passive (without any external energy supply) energy transport could be organized periodically. It is important during an accident in energy power stations or in other industry objects when energy supply is lost and a circulation pumps are stopped. If the condensation implosion event in the thermo-hydraulic system would be employed it makes possibility to design systems which can passively transport energy from a heat source to “cold” sinks. Though a heat pipe design is different from the described mechanism above, the energy transport initiated by condensation implosion event is similar to one in the heat pipe.

At Lithuanian Energy Institute an experimental program has been initiated whose goal is to develop a pulser component in which condensation implosion phenomena can be controlled and initiated at will. After a reliable pulser is developed, the follow up goal, is to implement this unique component in a thermal-hydraulic system designed to transport energy passively in a downward direction. The application possibilities of a pulser component will become more apparent once its basic parameters and operational characteristics are determined.

EXPERIMENTAL TEST FACILITY

A schematic of the experimental facility is presented in Fig. 1. The basic components of the facility are: the pulser itself, a 27 l cylindrical volume with an internal diameter of 0.25 m. In the current test configuration the cylinder is positioned on its side, steam enters the volume from the top, sub-cooled water is introduced at controlled rates from a central location in the bottom. The facility includes a steam generating boiler, a steam hold-up tank and a screw driven piston-cylinder arrangement for the controlled introduction of water.

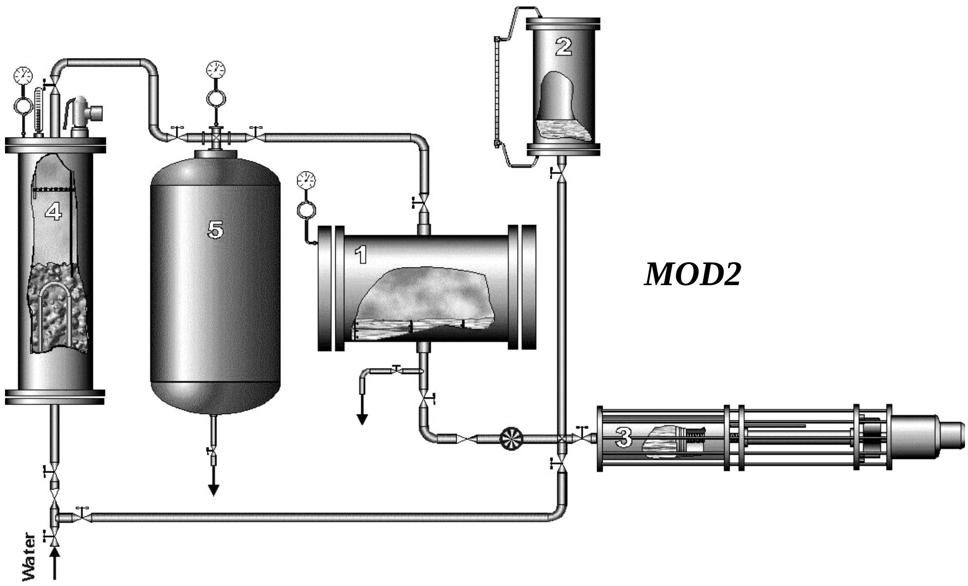

Fig. 1. Schematic of the MOD2 Pulser Test Facility: 1 - pulser; 2 - water supply tank; 3 - cylinder-piston for controlled introduction of water; 4 - boiler; 5 - steam storage tank

Tests were conducted at pressures from 1 to 5 bar above atmosphere. System pressure, liquid and vapor temperatures at various levels and the flow rate of the entering liquid are measured. Fig. 2 shows the spatial arrangement of TC's within the segment of pulser which is covered with water during tests. About 2 kg of water at the prevailing room temperature (~8 to 12 ^{o}C) is introduced during a test.

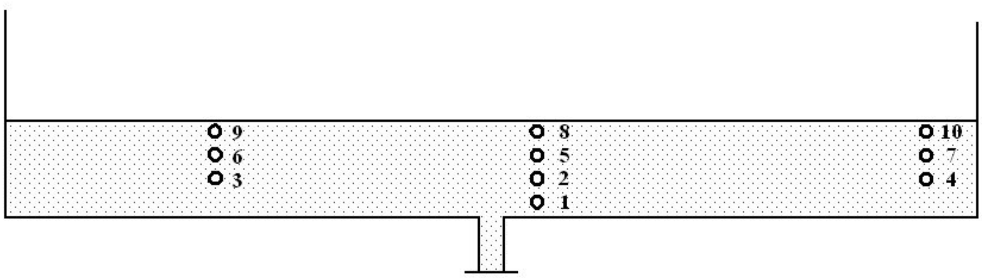

Fig. 2. Spatial distribution of TC's in liquid region of pulser: 1-10 – thermocouples

This paper presents test results obtained with the MOD2 simple pulser geometry for which the entering nozzles of both steam and water are installed flush with the shell of the pulser. The only variation in the flow geometry is the size of the entering water nozzle (1.7 and 1 cm ID). Tests with a “closed” and “open” steam generator have been conducted.

The test facility described above is a second generation facility. The first (MOD1) pulser test facility used gravity feed to introduce liquid water and included a plunger arrangement which could be used to supply “perturbation” surges of water to initiate condensation implosion pulses [5]. The MOD1 facility showed that the liquid introduction rate is one of the critical parameters, and that it could be used to suppress or initiate condensation pulses. At the same time it proved to be difficult to precisely control the water introduction rate with gravity feed. This lead to the adoption of the arrangement shown schematically in Fig. 1.

RESULTS

Sub-cooled liquid introduction rate

The most important test result is the demonstration that the perturbation of the liquid-vapor interface that is required for the initiation of condensation implosion pulses can be generated within the pulser itself. For specified steam introduction conditions (e.g. closed or open steam line, fixed location and the internal diameter of fluids introduction nozzles) condensation pulses can be initiated or suppressed by modulating the liquid introduction rate. Once a critical liquid introduction rate is exceeded steam implosion events will be generated with a high probability. Representative test results of two experiments are shown in Figs. 3 and 4. For these tests the line to the steam boiler was open and sufficient steam was generated to compensate the condensation rate to a stratified water-steam interface.

Fig. 3 shows a test, for which the pulser pressure was ~5.4 bar and a condensation implosion did not take place. In this test 2 kg of cold water was introduced from the bottom in ~ 60 s. The rate at which liquid rises in the lower segment of the pulser is recorded by the spatially distributed TC’s. Initially they measure the vapor temperature (148 ^{o}C), subsequently, as the water level rises to engulf them, they show the local liquid temperature. As shown in Fig. 2, the TC’s are distributed at four elevations. The t1 location starts to respond when 0.25 kg of water has been introduced, curves t2, t3 and t4 represent a water level of 0.75 kg, t5, t6 and t7 – 1.25 kg, t8, t9 and t10 – 1.75 kg. The data indicates that for this test there is practically no horizontal temperature gradient (the sets of 3 TC’s located at a given elevation measure almost the same temperature) and a well established, quasi-steady state vertical temperature gradient. The temperature of the introduced liquid is ~12 ^{o}C, thus the data shows that during liquid introduction appreciable heat-up occurs.

Fig. 4 illustrates the highly dynamic changes that take place when the liquid introduction rate is increased and a condensation implosion pulse occurs. The temperature traces prior to the occurrence of the pulse are similar to the “no-pulse” test but then, in a very short time, condensation rate rises exponentially until the entire liquid volume is brought to the saturation temperature. This terminates the condensation event and the resulting total steam condensation is so large that the boiler is not able to make up the lost steam so that the “post-pulse” pressure is lower. Note that the line to the steam boiler volume remains open throughout the test, thus the experiments illustrate that significant local pressure differences (in this case equivalent to the elevation of a 45 m water column) can be achieved inside a thermo-hydraulic system.

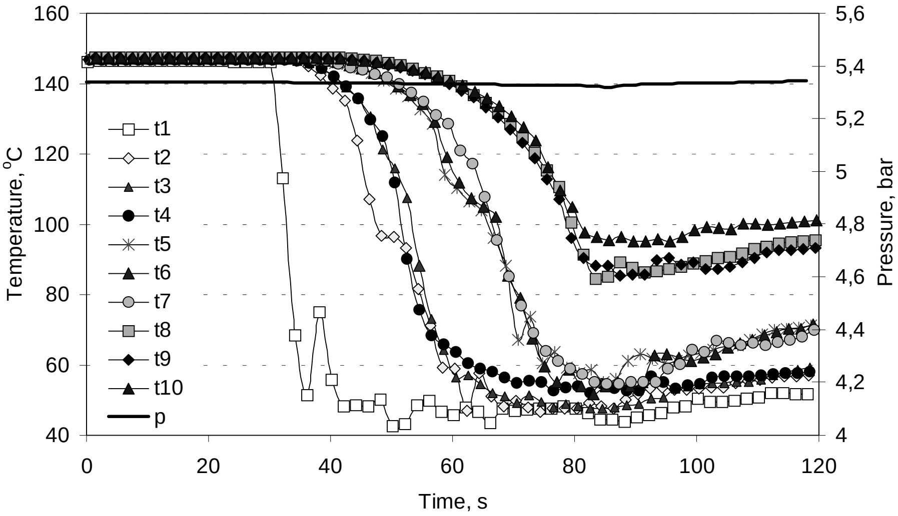

Fig. 3. Distribution of pressure (p) and liquid temperature (t1-t10 according Fig. 2). No pulse example

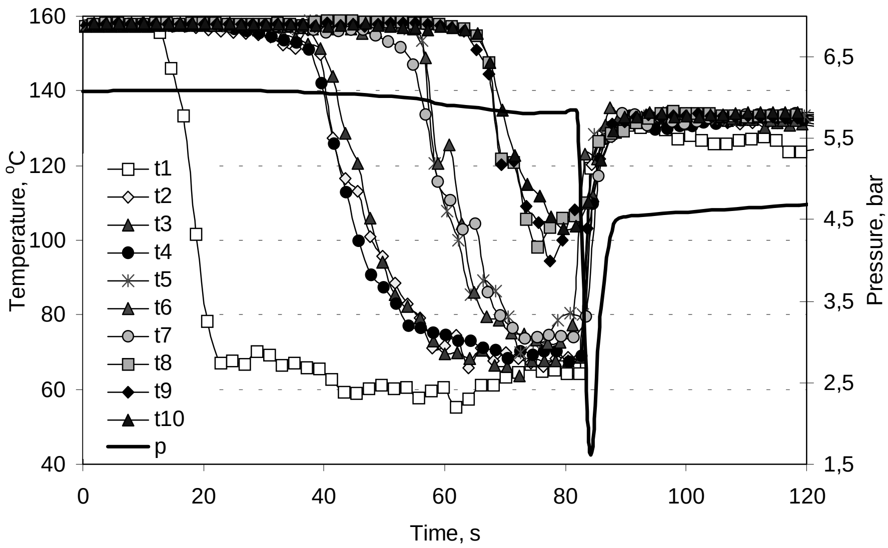

Fig. 4. Distribution of pressure (p) and liquid temperature (t1-t10 according Fig. 2).
Example with pulse

The processes leading to the condensation implosion event illustrated in Figs. 3 and 4 can be observed in more detail during tests for which the line to the steam boiler is closed. For these tests the initial steam content is known thus the total condensation rate can be inferred from the time dependent pressure measurement. Fig. 5 presents the measured pressure decrease for a series of tests which all start at an initial pressure of 3.5 bar and differ only in the liquid introduction rate. The rate of the entering liquid varies from 1.8 for the slowest to 2.3 kg/min for the fastest introduction rate. The entering flow is just one of the factors determining the degree of turbulence in the liquid layer, the other is the vapor friction and condensation generated shear at the steam-liquid interface. As Fig. 5 shows, changes in the entering flow rate on the order of ~10 to 15%, produces a shift to a different condensation mode.

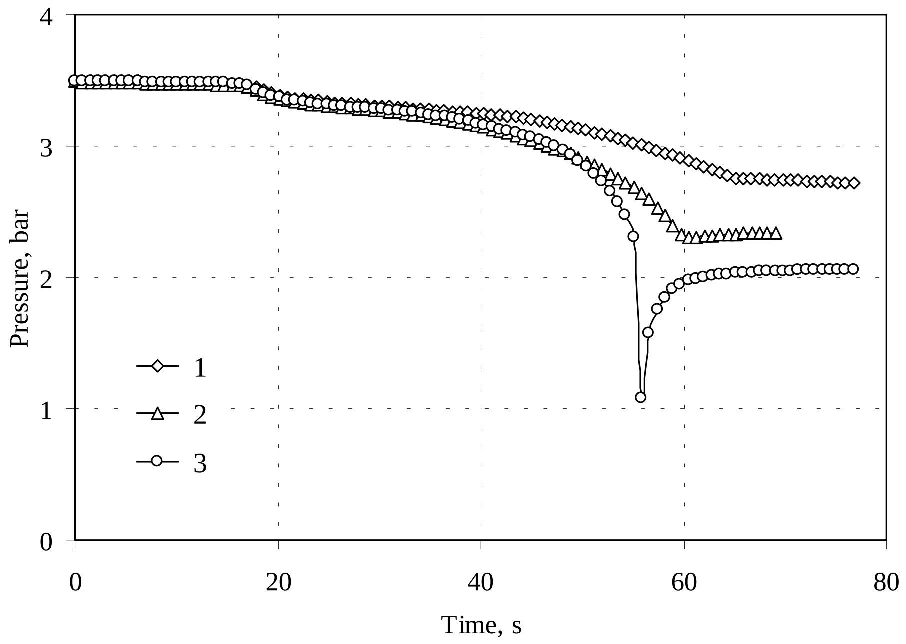

Fig. 5. Pressure distribution in the pulser with different liquid introduction rate: 1 – 1.8; 2 – 2; 3 – 2.3 kg/min (diameter of water entering nozzle 0.01 m)

Influence of system pressure

The system pressure during the tests varies from 1 to 5 bar above atmosphere. Selected representative test results obtained with a closed steam generator with different initial system pressure (2, 3.5 and 5 bar) are summarized in Fig. 6. The figure summarizes the total pressure drop from the initiation of sub-cooled water flow, to its termination. Note that a large pressure drop does not necessarily imply that a condensation pulse occurred. If the condensation rate was sufficiently intense that the inflowing water was heated as it entered (it will defined as fourth condensation mode further), pressure decrease was large but gradual. The “pulse/no–pulse” condition is indicated by using different black/white symbols respectively.

Fig 6. shows pressure drops of tests for which initial pressures where 2, 3.5 and 5 bar, but which were similar in all other aspects. The larger pressure drops produced when the test starts at a higher pressure are to be expected. The results also show that the critical flow rate, that is, the sub-cooled water introduction rate at which condensation pulses can be initiated, becomes larger with pressure. This trend reinforces the supposition that surface disruption depends primarily upon frictional and condensation caused shear. Shear stresses upon the interface are proportional to the square of those local steam velocities which are parallel to the surface. At lower pressures, comparable condensation rates generate higher steam velocities.

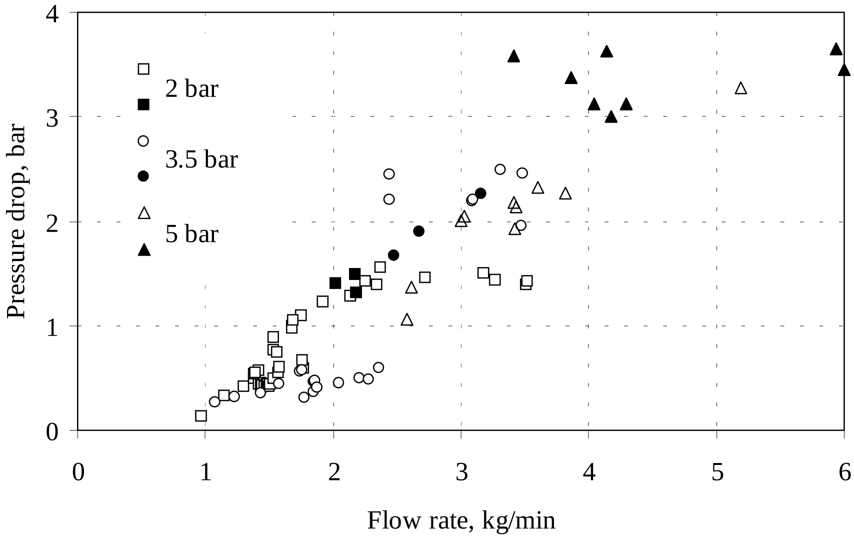

Fig. 6. Influence of initial system pressure for pressure change during introduction of liquid (diameter of water entering nozzle 0.017 m)

The tests with different water entering nozzle diameters (0.017 and 0.01 m) showed that the in-flow rate is indeed an important parameter, but the Re number at the entering nozzle is not a sensitive indicator of the turbulence in the liquid layer. Although the entering Re changes significantly (up to 70-80%) the critical flow rate remains very similar.

Condensation modes

The measurements performed to date make it possible to identify four distinct condensation modes. The conditions at which they occur is influenced by the pressure, the location and geometric properties of the liquid and steam introduction nozzles, but they have the same general characteristics and sequential dependence on the liquid introduction rate. For a given initial pressure and pulser flow geometry, the four condensation modes (taken in sequence for increasing liquid introduction rates) are:

1) At a low liquid introduction rate – nearly constant condensation on a smooth liquid-vapor inter face; water temperatures are stratified and quasi-steady.
2) As the liquid flow rate is increased, the interface becomes wavy. Condensation rate is higher, and it increases with time. A positive, apparently linear feedback coefficient between the condensation rate and the "waviness" of the surface is present.
3) After a specific critical introduction rate is reached, the gradually rising "wavy" condensation is transformed into a condensation implosion pulse. In effect, the positive feedback coefficient becomes exponential. As a consequence condensation shear becomes so strong that the continuous phasic inter-phase is shattered and the entire liquid volume reaches saturation temperatures. Condensation rate exceeds the inertial time constants of steam in the supply line and the pressure in the pulser drops suddenly.
4) If the liquid flow rate is increased further, surface waviness is initiated early, the liquid is heated while it is being introduced and a significantly sub-cooled liquid layer does not develop. For these conditions pulses do not occur, or they are relatively weak.

The time dependent pressure for representative tests during which one of the first three condensation modes dominated is shown in Fig. 5. For the upper test condensation (1st curve) rate is directly proportional to the nominal (geometric) vapor-liquid interface area and the curvature of pressure distribution reflects the change of the geometric area as the liquid region increases in the pulser. For the next test (2nd curve) the liquid inflow rate is higher, surface waviness is initiated and condensation rate increases faster then the nominal inter-face. Finally, at a still higher liquid introduction rate, the "wavy" condensation mode is transformed into a condensation implosion event (3rd curve). The final pressure, after the pressures in the pulser and steam supply tank have equalized, is proportional to the total amount of steam condensed during the test. An example of the fourth condensation mode is shown in Fig. 7. As seen in the figure, once waviness starts, the condensation rate is large, but reasonably constant. This leads to a significant integral pressure drop, but the pressure drop occurs gradually and/or parasitic weak pulses are generated.

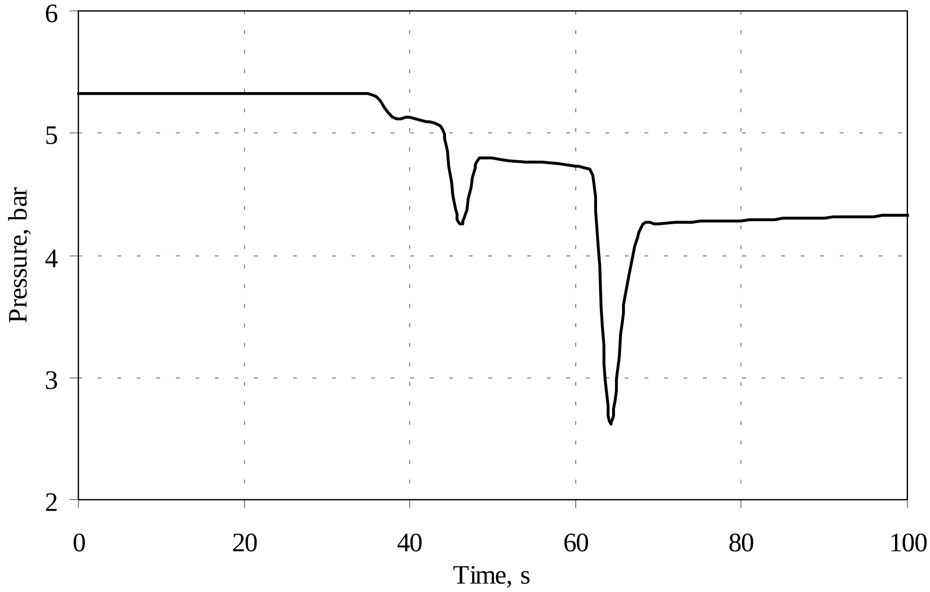

Fig. 7. Illustration of fourth condensation mode

CONCLUSIONS

An experimental facility whose purpose is to quantify the perturbation required to initiate condensation implosion events has been designed and constructed at LEI. The unique aspect of the current series of experiments is that they have shown a possibility to induce condensation implosion events in a horizontal cylindrical pulser solely by varying the introduction rate of sub-cooled water. Interface disruption is triggered when an increasing liquid-vapor inter-face generates a growing condensation rate that leads to larger vapor flows. Vapor flow and condensation induced shear initiate surface waves and when these exceed a critical growth rate complete interface disruption leading to a rapid condensation pulse. The dependence of this critical liquid flow rate on system pressure and geometry of liquid entrance nozzles has been explored.

The tests have shown that pulser can be designed in which the vapor-liquid inter-face perturbation required for the initiation of condensation implosions is generated internally and depends solely on the rate at which liquid is supplied to the pulser. That shows a possibility to generate large local pressure gradients, which can generate significant fluid flows.

Nomenclature

ID	inner diameter
LEI	Lithuanian Energy Institute
p	pressure, bar
t	temperature, ^{o}C
TC	thermocouple

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