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AN EXPERIMENTAL RIG AND INVESTIGATION OF STEAM GENERATOR TUBE LOADING DURING MAIN STEAM LINE BREAK

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Abstract

Steam generator tubes in the U-bend region vibrate due to secondary side cross-flow, resulting in fretting wear that reduces the margin of safety against failure. In the event of a main steam-line-break, a rapid blow-down of pressurised water produces a high-velocity steam-water flow across the tubes, which induces potentially catastrophic transient loading that is difficult to predict. Tubes in CANDU steam generators that cannot withstand the transient loading could leak irradiated primary side fluid into the secondary side, which passes outside of the containment. The objective of this experimental study is to develop a better understanding of the transient loading.

1. Introduction

During their normal operating life, steam generator tubes can be damaged by corrosion and mechanical wear at the tube supports [1]. Tubes in steam generators vibrate when subjected to cross-flow of secondary side coolant, particularly in the U-bend region. In order to minimise these vibrations, the tubes are supported by anti-vibration bars with small clearances between the tubes and their supports to allow for thermal expansion and manufacturing assembly. Such tube vibrations often result in fretting wear at the tube supports, thereby reducing the tube wall thickness and therefore the margin of safety against failure. A main concern of reactor safety is to ensure that radioactive materials produced by nuclear fission reactions during reactor operation are safely contained [2]. It is therefore essential that steam generator tube integrity be maintained.

A double-ended guillotine pipe break in the main steam-line of a CANDU steam generator is instantaneously followed by a rapid blow-down, in which heated pressurised water in the steam generator is brought to a superheated state by a very rapid depressurisation, and suddenly flashes to vapour. This phenomenon produces a huge increase in the flow rate and hence pressure drop, resulting in considerable transient drag loading on the tubes in the U-bend region. This transient and the associated tube loading are difficult to predict.

The objective of this research project is to address the potential for steam generator tubes of increased vulnerability, due to fretting wear or corrosion degradation, to rupture because of transient loading during a postulated main steam line break accident. The overall purpose of this project is to perform an experimental investigation of the transient blow-down loading of steam generator tubes in order to provide some physical insights and guidance for the development of predictive modelling tools. The experiments were conducted using a purpose designed and built experimental blow-down rig that implements a sectional model tube bundle. The paper presents the design of the rig and discusses the experimental results.

2. Experimental rig design

In order to carry out the steam generator blow-down simulations, an experimental rig was designed and built. A pictorial view of the design can be seen in Figure 1. The basic concept of the design is to have a static fluid reservoir containing liquid R-134a at the appropriate temperature and pressure conditions, a sectional model test section including a bundle of steam generator tubes, of which a cross-sectional view is shown in Figure 2, a pressure control device to suddenly release the pressure on the fluid reservoir, and a vacuum tank of sufficient volume that the blow-down transient is not controlled by rising downstream pressure. The pressure upstream and downstream of the pressure release device is monitored, as are the temperatures and the load on the tube bundle during the transient. Sight glasses upstream and downstream of the test section permit visual observation of the blow-down event as well as its recording using high-speed imaging.

The test section contains a tube bundle consisting of 6 rows of 12.7 mm diameter tubes in a normal triangular geometry with a pitch ratio of 1.36. The tube array geometry, pitch ratio and tube diameter are similar to those used in CANDU steam generators. The test section casing was designed so that the load cells are sealed from the R-134a using O-rings since their performance and durability upon exposure to any liquid could not be guaranteed. Basically, the design transfers the entire blow-down drag loading on the tube bundle to the force sensors while sealing the latter from contact with the R-134a. The device used for suddenly releasing the reservoir pressure to create the simulated blow-down is clearly a very important part of the design and non-fragmenting aluminium rupture discs that are set to rupture with a predictable opening pattern at a prescribed pressure difference of 585 kPa were employed.

2.1 Working fluid

In this study, refrigerant-134a was used as the working fluid in order to keep the costs down and simplify the required experimental facility, since it boils at around 21 °C under 585 kPa. The loading on the steam generator tubes during a blow-down is primarily a fluid drag force and is expected to scale with the dynamic head. Thus, fluid density and velocity are important scaling parameters and, in two-phase flows, the ratio of liquid-to-vapour densities is important. The liquid-to-vapour density ratio can be matched by setting the pressure of the working fluid. R-134a has a density ratio of about 35 at 26 °C and a pressure of 690 kPa, which is very close to that of steam-water at 257 °C and 4.5 MPa boiler pressure. For the sectional model tube bundle, the tube diameter and pitch ratio are also important in partially determining the bubble size. The model used in these experiments has essentially full sized tubes with the full-scale pitch ratio, in compliance with the requirement for geometric similarity. Thus R-134a was chosen as a reasonable operating fluid for these blow-down simulation experiments.

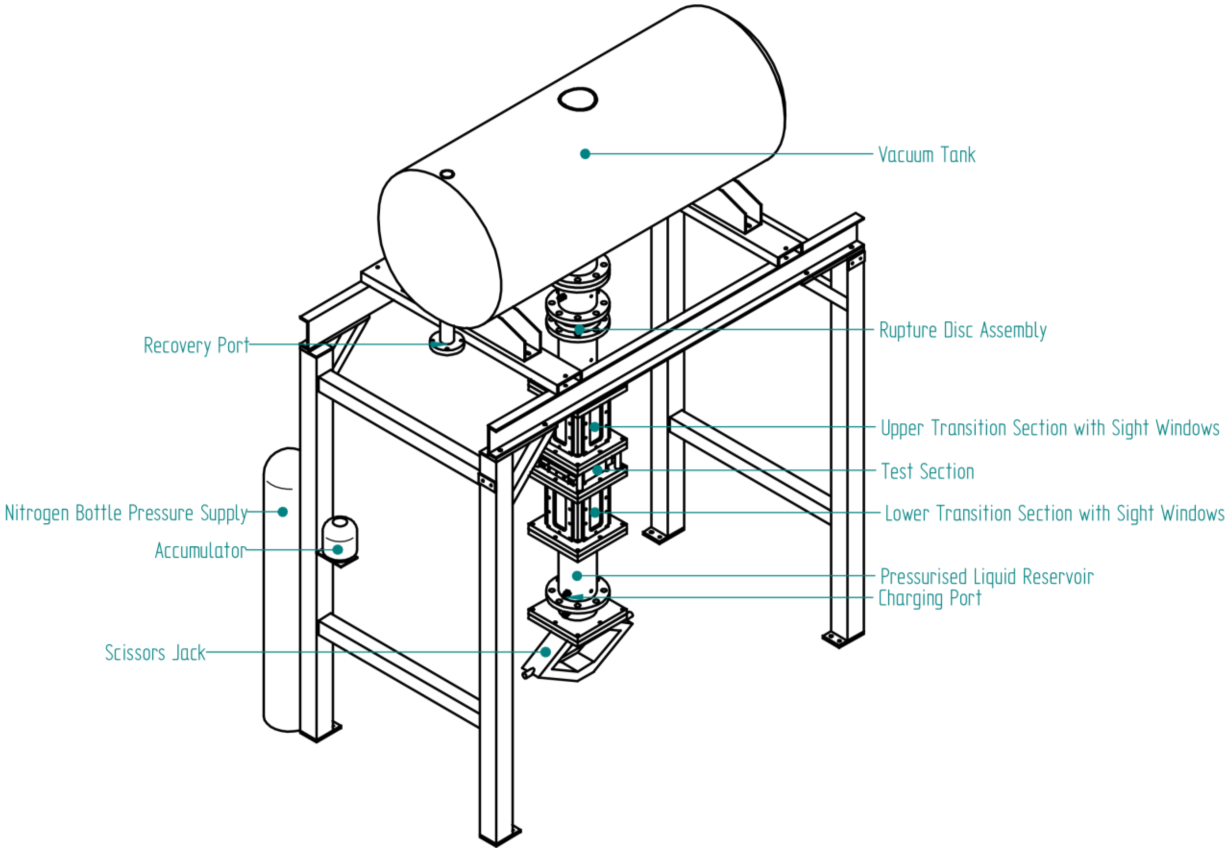


Figure 1 Pictorial View of Experimental Rig.

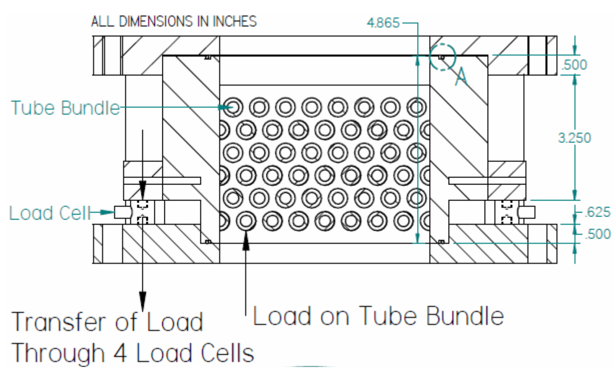


Figure 2 Tube Bundle Detail Drawing.

2.2 Pressurisation system

The purpose of the nitrogen gas cylinder and accumulator system illustrated in Figure 1 is to produce fine pressure control to trigger the blow-down. The hydraulic diaphragm accumulator of 2.8 litres capacity is divided into two compartments horizontally separated at the centre by an elastomeric diaphragm. The bottom section of the accumulator is connected to the pressurised liquid reservoir, and the top section is connected to the nitrogen gas cylinder. In order to activate the blow-down, the bottom compartment of the accumulator is first allowed to fill up with R-134a and the top compartment is then pressurised using the nitrogen cylinder until the required pressure is achieved. The advantage of using this system is that it permits precise control of reservoir pressure, and therefore disc rupture, without introducing any foreign substance to the system. In particular, the problems associated with nitrogen contamination are avoided.

3. Determination of rupture disc burst instant

In order to properly analyse the fluid behaviour following the sudden break of the rupture disc, the steady-state conditions upstream of the rupture disc before the sudden depressurisation need to be accurately determined. Furthermore, given the significance of the phenomena occurring during the first few milliseconds following disc rupture, establishing an objective and repeatable method of determining the precise instant of rupture disc opening is very important. A good estimate of the starting point of the blow-down in the time domain allows for an improved evaluation of the physical phenomena such as signal phase lags, time delays associated with wave propagation speeds, and liquid volume effects. The initial height of the liquid volume inside the blow-down rig just before disc rupture is determined through a thermodynamic analysis of the R-134a at its temperature and pressure conditions. Based on the analytically determined thermodynamic conditions of the pressurised fluid inside the blow-down rig, a methodology has been implemented that permits determination of the opening instant of the rupture disc.

Barták [3] concluded systematically that the propagation velocity of the depressurisation wave during the initial stages of a blow-down does not differ from the local sound velocity, which forms the basis of the current approach for establishing the time of rupture. It must be noted that the computed estimates for the speed of sound are only valid for a short period of time directly following disc rupture, and are unsuitable beyond the point of significant vapour generation in the liquid domain. The effect of vapour production on the speed of sound is substantial, the sonic velocity being lower in a two-phase mixture than in a liquid or vapour phase alone. As the void fraction increases with the development of the blow-down flow, the sonic velocity estimates are expected to deteriorate. The damping also increases as a result of vapour formation, which slows down and reduces the amplitude of the travelling pressure waves. From the speed of sound, the time required for pressure wave propagations is calculated based on the distances from the locations of the events of interest and the corresponding measurement locations. Figure 3 displays computed times after disc rupture for the main compression waves, rarefactions, and pressure reflections for a sample experiment.

The estimated time required for the wave generated at the rupture disc to arrive at the dynamic pressure transducer directly downstream of the rupture disc is 0.9 milliseconds, as indicated in Figure 3. Consequently, the first significant rise in the mean pressure signal was set to occur 0.9 milliseconds after the initiation of the transient blow-down. The noise in the pressure signal is about ±21 Pa, and the first detectable pressure rise was usually of the order of 1.4-2 kPa. This procedure was found to be highly repeatable for all experiments, as shown in Figure 4, and provided a consistent means of accurately establishing the acquired signals in the time domain. The determination of the starting time of the transient then allows for methodical evaluation of important post-blow-down phenomena. The mean pressure signal behaviour at the instant of rupture was found to be very similar across all experiments, unaffected by factors such as the signal sampling rate and the initial pressure magnitude.

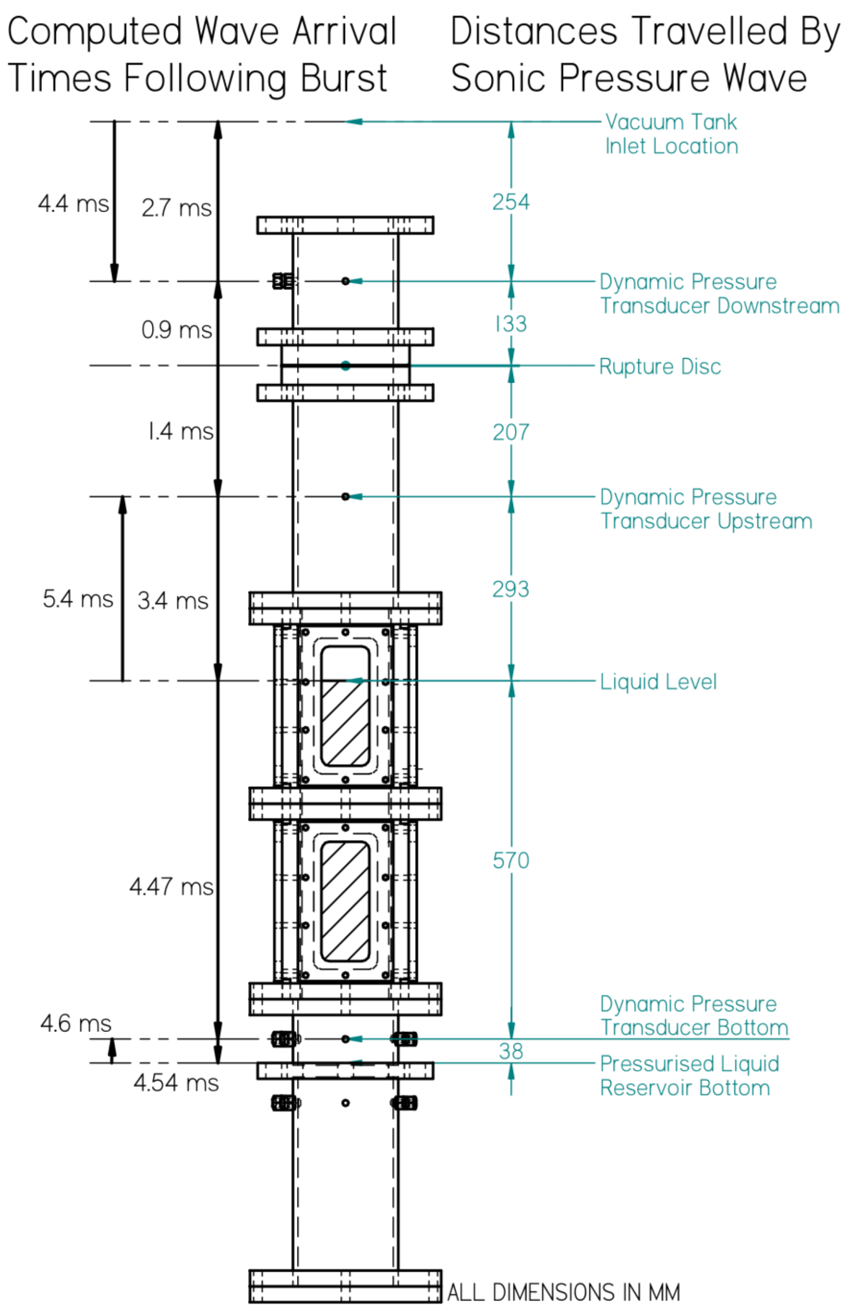


Figure 3   Wave propagation times for large volume experiment without test section.

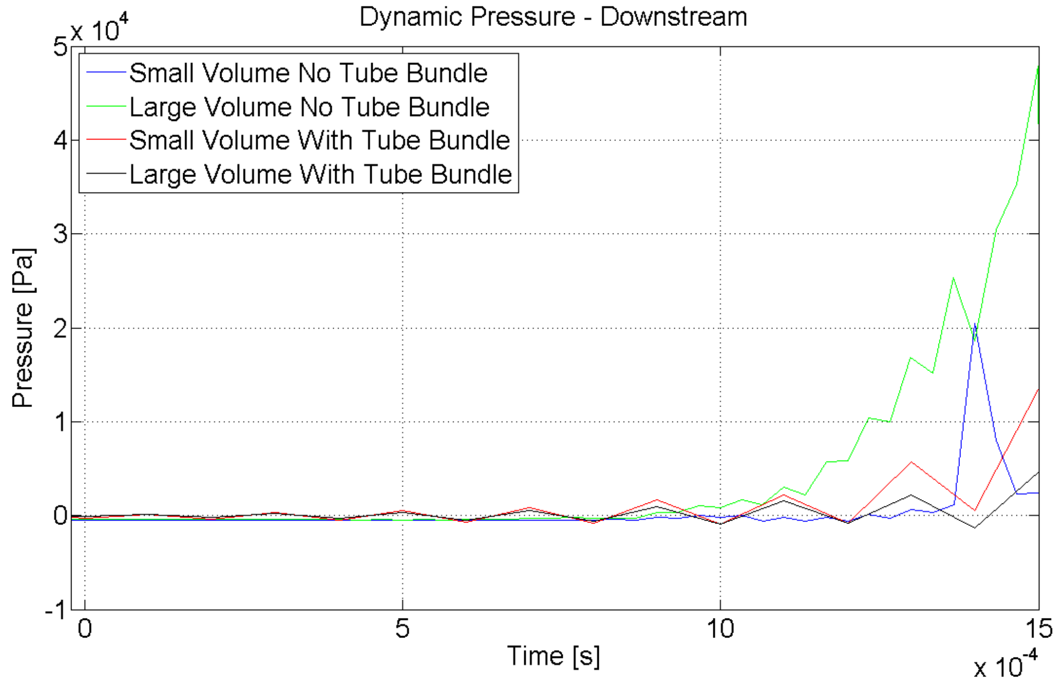
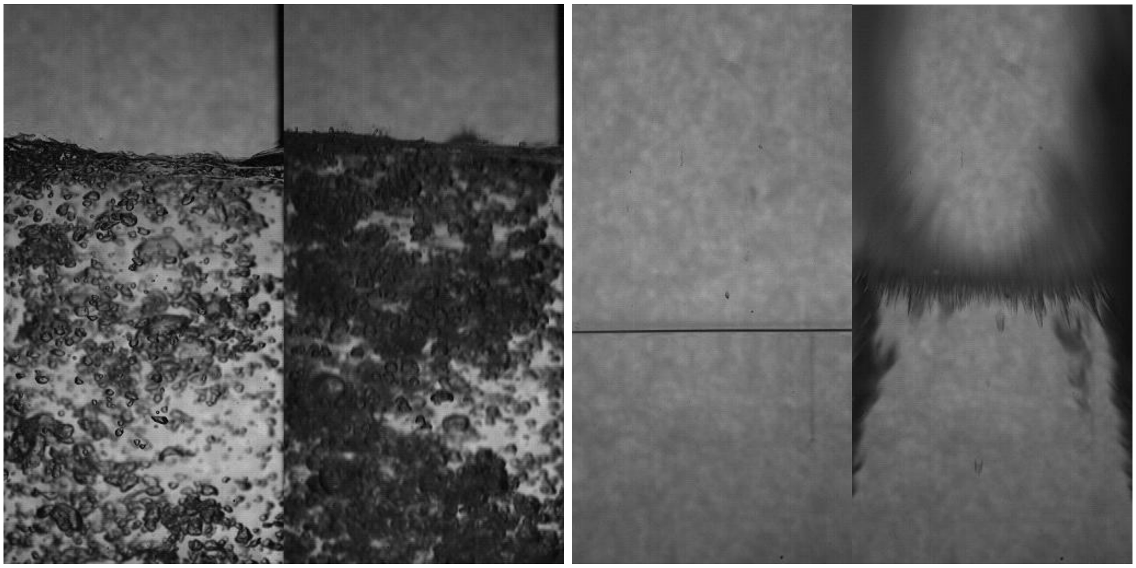


Figure 4 Graph of downstream pressure trace in the time domain. (Small volume: 4.5-5.5 L; Large volume: 11.5-14.6 L)

4. Discussion of experimental results

The starting point of the blow-down experiments was the opening of the rupture disc, which subjected the pressurised fluid to a sudden pressure reduction that accelerated the two-phase mixture upwards towards the break location and into the vacuum tank. The initial flow rate is limited by the fluid inertia, and the pressure loss is transmitted as a pressure wave during the subcooled depressurisation. When the liquid pressure falls sufficiently below the saturation value corresponding to the initial temperature, in the superheated region, vapour nucleation occurs. The delay time associated with nucleation is dependent on the rate of depressurisation. Following the initiation of the explosive phase change behaviour, the fluid enters a two-phase transition regime during which the vapour-liquid ratio begins to increase.

The superheated liquid that is created immediately following the depressurisation exists in a meta-stable state, and the ensuing volume production drives the two-phase mixture towards thermodynamic equilibrium. In a perfectly homogeneous system, nucleation arises spontaneously due to thermal fluctuations and intermolecular interactions, and the flashing displays bulk boiling behaviour. Factors such as surface roughness and liquid impurities increase nucleation heterogeneity, and reduce the time available for pressure relaxation before bubble formation. In such cases, the flashing would occur as liquid-vapour interface boiling, and heterogeneous boiling at liquid-solid boundaries. In real steam generators, the nucleation would occur at the metal surfaces due to sizeable surface imperfections, and the same phenomena were seen in the present blow-down experiments. The primary vapour generation mechanisms observed were the activation and growth of bubbles either pre-existing in the bulk liquid, or originating from surface cavities, and vapour generation in the bulk liquid was less evident. Figure 5 shows two vapour generation cases with bubbles acting as sites for premature nucleation in the first case and heterogeneous boiling at the vessel walls in the second case.



(a) **(b)** **(c)** **(d)**

Figure 5 Nucleation Mechanisms: Interface Boiling (a, b), Heterogeneous Boiling (c, d).

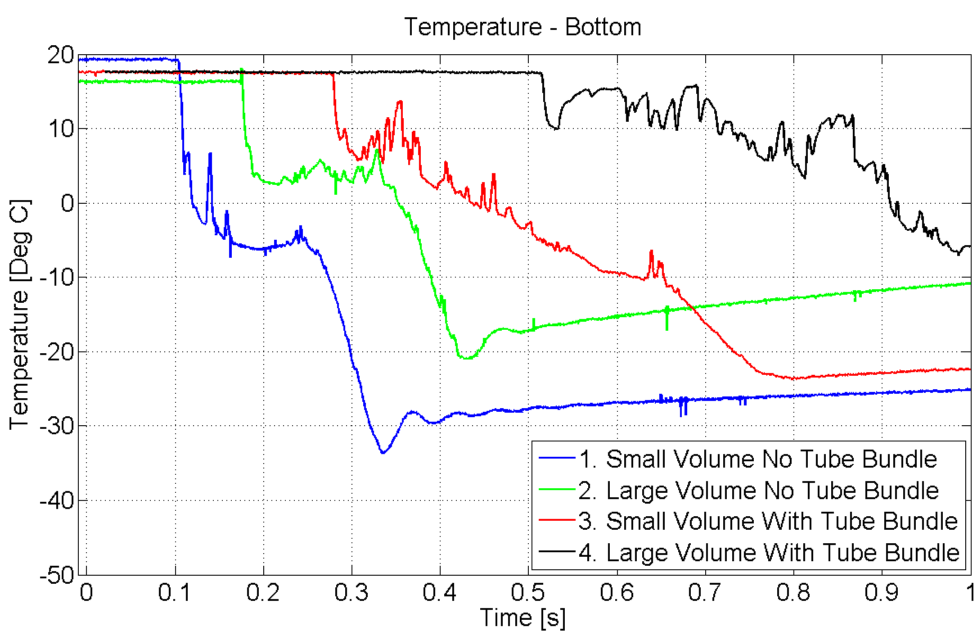


Figure 6 Temperature vs. Time (Bottom Location; Initial Temperature: 16.2-19 °C; Initial Pressure: 554-579 kPa).

The effects of volume of liquid and presence of the tube bundle on thermal response can be seen in Figure 6. The most notable feature is the difference in behaviour caused by the presence of the tube bundle. The temperature response during the first two experiments displays very similar characteristics, and the same applies to the two experiments performed with the test section installed. For the first two experiments, the temperature undergoes a sudden drop, followed by a quasi-steady stage that accompanies the phase change. The temperature then decreases at a slower rate towards a temperature minimum, before increasing gradually towards the equilibrium state, following a steady-state saturation path. In contrast, the temperature behaviour with the tube bundle installed shows a more gradual decrease, with temperature spikes indicating a higher degree of mixing between the liquid and vapour phases. This condition persists until steady-state conditions are established, and the temperature follows a saturation path. There appears to be two effects of increasing the initial volume of liquid; a longer duration of the early isothermal stage preceding the temperature drop, and a higher temperature for the ‘quasi-steady’ and steady state stages.

Heat transfer from the liquid to the vapour interface controls the vapour generation process. Therefore, the initial liquid temperature level determines the magnitude of the driving force for the liquid-to-vapour transition. Higher temperatures produce more rapid phase transitions, which result in shorter transients. This effect is observable in Figure 6, where the higher temperature produces more rapid phase change, and the lower temperature produces a higher degree of superheating. The transient temperatures deviated significantly between the liquid and vapour phases during the blow-down. The vapour phase approached saturated conditions with respect to the system pressure quicker than the liquid phase, which remained superheated as the transition phase change took place. From the temperature results, and particularly, the behaviour shown in the third experiment, it appears that the degree of departure from thermodynamic equilibrium, reflected in the rate of fluid expansion, is dependent on the volume to discharge area ratio. When the ratio is small, as is the case for the first two experiments, and the last experiment when the liquid surface is above the tubes, the rate of fluid expansion is relatively high. When the liquid surface is below the tubes however, the exit area of the flow is dramatically reduced, which provides sufficient time for mixing and heat transfer between the phases, such that thermodynamic equilibrium is approached quicker, and maintained throughout the latter stages of the blow-down transient.

5. Difficulties encountered with instrumentation and dynamic measurements

Despite providing valuable information concerning the dynamic pressure behaviour during the transient stages of the blow-downs, the pressure transducers did not behave entirely satisfactorily, and there are some segments of the results that cannot be explained physically, especially for the two pressure transducers closer to the rupture disc. The occurrence of high-frequency oscillations observed immediately following the opening of the rupture disc raises the question of whether the acceleration compensation in the pressure transducers is capable of handling the large shock-loads generated in these blow-down experiments. When a rarefaction wave passes along a pipe, the relief on the internal pressure could cause the pipe to contract in diameter, and similarly, a compression pulse would produce a sudden pipe expansion. These sudden pipe movements subject the pressure transducers to axial accelerations. Without acceleration compensation, movement towards the flow would produce an increased pressure effect, and movement away from the flow would produce decreased pressure. This behaviour is observed in the dynamic pressure results. The acceleration sensitivity of the sensors is 7 Pa/G, but it may be that the acceleration rates in the present experiments are above the range of the integrated accelerometers, overwhelming the acceleration compensation.

The dynamic pressure signals directly upstream of the rupture disc, and possibly the downstream pressure transducers as well, were substantially degraded by sudden temperature changes produced during the initial stages of the blow-downs. One of the major effects limiting the accuracy of piezoelectric transducers is their sensitivity to thermal loading effects [4]. Changes in thermal load affect the response of piezoelectric pressure transducers through the corresponding deformation of the transducer and through the resultant effect on the sensitivity. Upon exposure to thermal shock, a temperature gradient is set up in the transducer material and the metal surrounding it. If the corresponding thermal expansion deforms the transducer to the extent that the quartz crystal is affected by this deformation, the pressure transducer registers a response even if the pressure were to remain constant. The thermal contractions caused by the sudden temperature drop during depressurisation transients are expected to produce apparent dynamic reductions in pressure thereby explaining the spurious pressure reductions below 0 absolute pressure.

It appears as though the thermal barrier covering the pressure sensing membrane of the transducer was not sufficient for insulating the pressure sensor from thermal shock. The thermal insulation coating apparently performed well for the commissioning tests. However, the experimental results indicate that the performance of the thermal insulation degraded with continued exposure to depressurisation blow-downs.

A comparison of static and dynamic pressure measurements at the bottom of the pressurised liquid reservoir is presented in Figure 7. Since the acceleration and thermal shock effects observed for other sensors were not present at this location, the dynamic pressure signal should closely represent the actual pressure variation inside the system during the transient stages of the blow-down. On the other hand, the pressure transients are too fast for the static pressure sensor. The static sensors accurately provide the initial pressure conditions before rupture as well as the slowly changing pressures after the transient is complete. However, there is a time delay associated with the response to the rapid transient, after which an amplified change in pressure is immediately produced, overshooting the dynamic pressure signals.

Following the initial sudden response, the overall trends and slopes of the static sensor pressure variations are generally in agreement with the dynamic signals. Furthermore, the phase lag between the two sensors remains consistent throughout the depressurisation, indicating that the static pressure sensors are capable of following the pressure behaviour after a certain time delay. From these results, it is concluded that the static pressure sensors work well except when subjected to an abrupt change in pressure where the time delays and pressure amplitudes are no longer accurately represented. On the other hand, the dynamic pressure transducers react exactly when expected after disc rupture based on the agreement of calculated rarefaction wave passage times with the registered depressurisations. Thus, it appears that these work well as long as the pressure is changing rapidly enough but tend to deteriorate towards the end of the blow-down where the pressure changes occur at a slower rate. In conclusion, both static and dynamic transducers seem to behave as expected, with the static sensors failing to capture rapid transients, and the dynamic transducers losing accuracy for slow pressure variations.

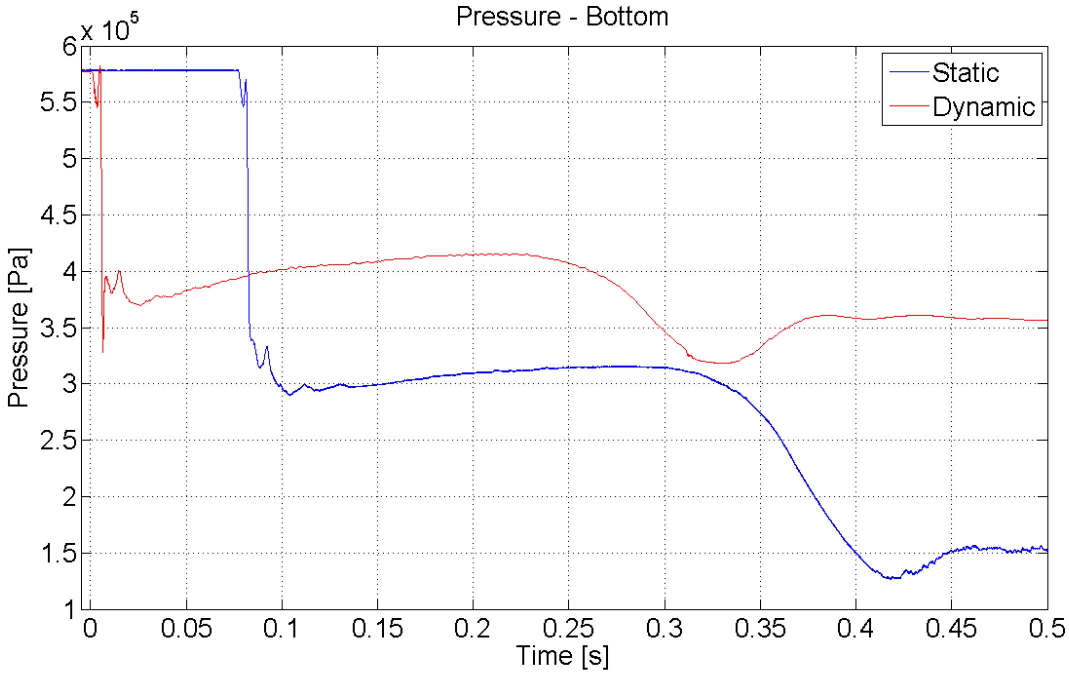


Figure 7 Pressure vs. Time (static & dynamic measurement comparison).

The dynamic tube bundle loading results produced by the load cells for each of the two experiments in which the liquid surface relative to the tube bundle was varied are compared in Figure 8. Unfortunately, the effect of fluid drag loading on the tubes is overwhelmed by other phenomena. The load cell response in the first 5 milliseconds of the transient is driven by the shock response of the system to the disc burst. The oscillations seen on the curves were determined to be a result of inertial effects, occurring at 35 Hz, consistent with acceleration measurements taken on the test section. The mean trends, which are changing relatively slowly and seem to indicate compressive loading on the load cells, cannot be explained in terms of the blow-down physics.

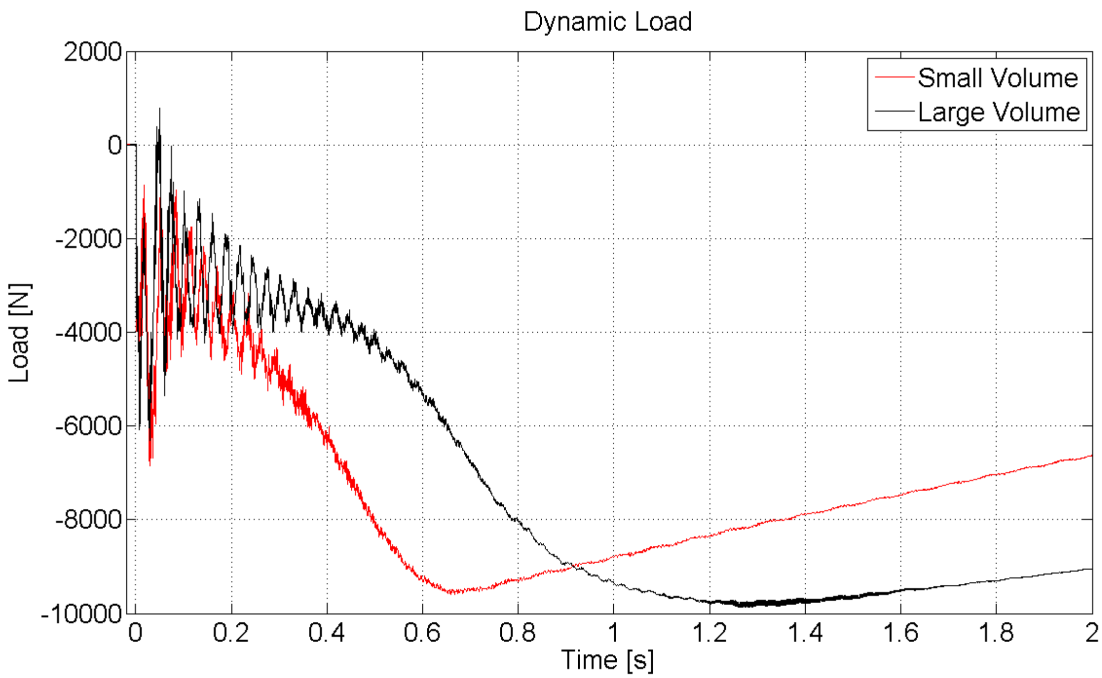


Figure 8 Load vs. Time.

6. Conclusions and recommendations

There has been much work in the literature investigating the blow-down phenomenon, with particular attention paid to predicting the discharged critical flow. Very little experimental research work has been performed on the transient tube loading effects during such phenomena, and the available published works are mostly numerical attempts that have produced mixed contradictory results. Hence, tube loading during a main steam line break remains a phenomenon that is difficult to predict. This experimental project was devised to study the effect of a simulated blow-down on tube loading, and assist in developing a better understanding of the transient loading and its prediction, such that structural tube failures can be avoided. An experimental rig was designed and constructed such that experimental investigations could be carried out. Using R-134a as a working fluid, the experiments could be performed at ambient conditions, greatly reducing the cost associated with heating and safely containing pressurised water at steam generator conditions. The rig was instrumented such that thermodynamic behaviour could be investigated through pressure and temperature response, and load cells were installed on the test section for tube loading measurements.

The thermodynamics of the system were assessed, and the effects of various parameters on the blow-down behaviour were established. Unfortunately, it was discovered that large shock-loads associated with the sudden violent nature of blow-downs did not allow proper fluid drag loading measurements to be obtained. Shock induced vibration of the experimental rig distorted the load signals as determined using accelerometers, and the mean dynamic loads remained unexplainable in terms of fluid drag loading phenomena. The experimental rig design is capable of simulating the thermal hydraulics of a steam-line-break in a steam generator very adequately, and confidence in the design has been gained through completion of the experimental phase of this project. In order to be able to obtain fluid dynamic tube loading characteristics, an alternative method of measuring the loads needs to be implemented.

Potential solutions involve the insertion of additional pressure transducers upstream and downstream of the test section. The pressure drop across the tubes could be monitored, and information regarding the pressure loading on the tubes would be extracted from the results. Alternatively, instantaneous dynamic loads could be measured using properly calibrated strain gauges. In order to obtain reliable dynamic pressure measurements, errors associated with vibration and thermal loads need to be eliminated. The acceleration effects can be controlled by simultaneously measuring the accelerations and accounting for the vibration by subtracting the corresponding signals from the pressure measurements. Thermal effects can be minimised by ensuring the durability of the insulation coating through reapplication between experiments, installing special adapters designed to minimise thermal effects, or acquiring 'thermodynamic' pressure transducers in which the sensitivity to thermal shock is minimised through water-cooling techniques.

7. Acknowledgements

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8. References

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