

Heat balance characteristics of a pressure vessel

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The study of heat balance in a pressure vessel is an important research area for energy conservation. In the present study, experiments are conducted to measure the heat input, heat energy utilized and heat loss for different volumes of water filled in a pressure vessel. Experiments are conducted on a pressure vessel of volume 0.008 m³ (8 l) filled with 1, 2, 3 and 3.7 kg of water at 12.5%, 25%, 37.5% and 46% of its capacity respectively. Two approaches are adopted to determine the optimum condition of the pressure vessel. In the first approach, the pressure vessel is insulated and in the other approach it is non-insulated. For both cases, vessels of similar capacity, make and design are used. Outer surface of the vessel is insulated with asbestos rope, clay and cow-dung bindings. There is not much difference in heat input and heat utilization for insulated and non-insulated vessels when the water level is only about 12.5% volume. In other cases, the insulated vessel consumes more heat input than the non-insulated vessel. When the non-insulated pressure vessel is filled with 46% of its volume by water, it utilizes a maximum of 30% of total heat supplied. From the experimental results, polynomial equations are developed for the heat input (Q_i), heat utilized (Q_u) and heat loss (Q_l) in terms of mass of the water taken in the vessel under non-insulated and insulated conditions. The equations obtained are validated for different water levels in the same vessels with new sets of experiments.

Keywords: Energy conservation, heat balance, insulated and non-insulated conditions, pressure vessel.

THE pressure vessel is widely used for cooking purpose around the world. It is essential to understand the heat balance characteristics of the pressure vessel to conserve energy in daily life and to extend the applications of isochoric heating process.

Das *et al.*¹ have conducted studies to determine the boiling characteristics of food items. Radha Raghunath and Nambi² conducted an experiment to study leachability of lead by tap water and tamarind solution from pressure vessels, while cooking with and without a safety valve.

Energy and pressure requirements for processing foods as affected by product moisture content and extruder barrel temperature have been studied by Bhattacharya and Hanna³. All these studies are concerned more with the thermal properties of food items. The present study is focused on heat balance of the pressure vessel in terms of heat input (Q_i), heat utilized (Q_u) and heat loss (Q_l) for energy conservation.

Vijayaraghavan and Goswami⁴ presented the applications of organic working fluids for a combined power and cooling cycle. The first law of thermodynamics gives a good solution to the expected performance of a cycle and it can help assess the overall efficiency of the cycle⁵. Campbell *et al.*⁶ highlighted the importance of policies for electrical energy savings and efficient energy utilization in power planning. They have also mentioned that a reduction of 20% in the growth trend of electricity consumption by the industrial customers would save US\$ 10.4 billion over the next 20 years, with a potential reduction of 1.6 million t/year of CO₂. Purohit⁷ presented test procedures for characterizing box-type and a family-size parabolic concentrator solar cooker, based on detailed experimental studies. His study was supported by a number of experiments carried out at New Delhi (lat. 28.56°N, long. 77°E) under various climatic and operating conditions round the year. Jiang *et al.*⁸ studied the bubble growth period, bubble growth rate, bubble detachment period and forces acting on the detachment. They have generated and presented the governing equations for bubble growth with computational results. Ramesh and Srinivasa Rao⁹ estimated the preliminary cost of cooking rice at a pilot scale as US\$ 0.17 per kg. They found that with necessary sealing at the outlet of the cooker, the cost can be reduced to US\$ 0.1 per kg. Kaygusuz¹⁰ studied the energy situation of the developing countries for sustainable development. He projected that about 342 million people will have no access to electricity in India by 2020; this number was 404 million in 2009. The present study is carried out to understand the heat transfer efficiency in an aluminum-based pressure vessel available in the market. The study also facilitates to find the efficiency of constant-volume heating process for developing particular steam pressure in a pressure vessel.

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Materials and experimental set-up

Experiments are conducted on a pressure vessel to explore its heat transfer characteristics for steaming different masses of water. In the first step the heat balance of the pressure vessel is estimated. Secondly, the effect of insulating the circumference (body) of the vessel on energy consumption is studied. Aluminum-based pressure vessel of volume 0.008 m^3 has been considered for conducting the experiment. The vessel is equipped with a pressure gauge and a thermocouple to measure the steam pressure and temperature. The pressure gauge is capable of indicating a maximum steam pressure of 7 bar at a least count of 0.1 bar. The thermocouple is connected with a digital temperature indicator having a resolution of 1°C . The experimental set-up consists of a gas stove integrated with an LPG (30% propane and 70% butane) container, electronic weighing scale and the vessel with thermocouple and pressure gauge. The LPG stove discharges gas (0.16 kg h^{-1}) so as to supply 2.2 kJ/sec of heat energy, when used with high-flame condition. The data have been obtained from the information catalogue issued by the manufacturer of the gas stove in collaboration with the LPG distributor. Validity of the data has been confirmed with the LPG distributor (calorific value of LPG: $49,786 \text{ kJ kg}^{-1}$) and stove manufacturer. The experiments are carried out in a steady state, high-flame condition only.

The experiments on insulated and non-insulated pressure vessels are conducted in the same ambient conditions. The air flow is not significant on heat balance since the experiments are conducted in a closed room. Heat energy is supplied with flow of LPG at constant rate. Effects of pH value and salt contents of water are negligible. Schematic arrangement of the experimental set-up is shown in Figure 1.

Methodology

The heat energy consumed during the experiment is obtained from the LPG consumption rate and the duration when the burner is 'ON'. These values are also verified by measuring the weight of the stove with LPG container before and after each experimental run. The pressure vessel is initially filled with 1 kg of water (12.5% volume of the vessel). An electronic weighing scale is used to measure the mass of the contents in the vessel at a particular instant. A digital stop watch is used to measure the heating time and whistling time in seconds. Vessel with water is heated; water in the vessel evaporates and the accumulation of steam causes increasing in pressure. When the steam pressure reaches a maximum value in the vessel, it lifts the control valve. This maximum pressure point is called 'whistling point', here the steam at maximum pressure starts leaving the vessel to the atmosphere through the control valve. Pressure of the steam in the vessel gradually reduces as the steam is leaving the vessel. At a

particular pressure of the steam, the control valve sets back (drops down) to arrest the steam flow; pressure of steam at this particular point is called minimum pressure (end of whistling point). Duration over which the control valve is in lifted position or the steam is permitted to leave the vessel to the atmosphere is termed as 'whistling time'. Initially 'heating time' is the time duration from the start of heat supply to the end of the first whistling point. After the first whistling time, 'heating time' is the duration from the end of the first whistling point to end of the next whistling point. The experiment is conducted by heating the vessel continuously at a constant high-flame position. The following quantities are measured:

- Initial temperature of water ($^\circ\text{C}$) using a thermometer.
- Heating time (sec) to reach the maximum steam pressure at which the control valve is lifted to release steam (whistling point).
- Pressure and temperature at the whistling point.
- Mass at whistling point.
- Whistling time (sec).
- Pressure and temperature at the moment of drop of the control valve (end of the whistling point).
- Mass at the end of whistling point.
- Heating time for developing maximum pressure and temperature to reach the next whistling point.

The experiment is repeated for 2 kg (25% of volume of the pressure vessel), 3 kg (37.5% of volume of the pressure vessel) and 3.7 kg (46% of volume of the pressure vessel) of water. Based on the heating time (t) measured between each end of the whistling points, the heat input (Q_i) (kJ) is obtained as

$$Q_i = \text{Rate of heat supply} \times \text{heating time.}$$

$$Q_i = 2.2 \times \text{heating time.}$$

$$Q_i = 2.2 t. \quad (1)$$

The temperature and pressure at each whistling point are observed to be constant as 116°C and 2.1 bar (absolute pressure) respectively. At this point the steam is in wet condition; its dryness fraction (x_1) is given by

$$x_1 = \frac{\left(\frac{V}{m_1}\right) - v_{f_1}}{v_{fg_1}}, \quad (2)$$

where v_f is the specific volume of water (m^3/kg), v_{fg} the specific volume of steam (m^3/kg), V the total volume of the vessel (0.008 m^3) and m is mass of water or water vapour mixture in the vessel (kg). The enthalpy of the water and vapour mixture at the whistling point (H_1 ; kJ) is

$$H_1 = m_1(h_{f_1} + (x_1 h_{fg_1})), \quad (3)$$

where h_f is the enthalpy of water in the vessel (kJ/kg), and h_{fg} is the enthalpy of wet steam (kJ/kg). Similarly, the temperature and pressure at the end of each whistling are observed to be constant as 112°C and 1.7 bar (absolute pressure) respectively. At this point also the steam is in wet condition; its dryness fraction and enthalpy (kJ) are estimated as x_2 and H_2 respectively. Useful enthalpy rise of the contents of the vessel (heat energy utilized, Q_u (kJ)) is

Q_u is the heat energy effectively utilized by the vessel for increasing the pressure of water and steam mixture from minimum pressure to maximum pressure.

Q_u = Enthalpy of water and steam mixture at the point of maximum pressure of steam (whistling point) in the vessel – enthalpy of water and steam mixture at the point of previous minimum pressure of steam (end of previous whistling point) in the vessel.

$$Q_u = H_{1S} - H_{2P}. \quad (4)$$

Here, H_{1S} is the enthalpy of the contents of the vessel at the current whistling point (in general '1' represents the whistling point and 'S' represents 'succeeding value'). H_{2P} is the enthalpy of contents of the vessel at the end of previous whistling point (in general '2' represents the end of whistling point and 'P' represents 'preceeding value'). The term 'heat utilized' accounts for the heat energy used for increasing the pressure of steam from minimum to maximum. Heat energy supplied during the whistling period is accounted in heat input, but is not considered in heat utilized. The useful enthalpy rise of the steam during heating time is the cause of increasing pressure of the steam, which leaves to the atmosphere after reaching the maximum pressure. Hence, the amount of heat energy carried away by the steam to the atmosphere during the whistling period is accounted neither in heat utilized nor in heat loss. It has been already included during the heat input in the form of heat utilized (enthalpy raise). The difference between the heat input and effective enthalpy rise of the mixture of water and steam in the vessel is the heat loss (Q_l) to the atmosphere through the circumference (body) of the vessel.

$$Q_l = \text{Heat input} - \text{heat utilized.}$$

$$Q_l = Q_i - Q_u. \quad (5)$$

Experiments are also conducted to determine the effect of insulating the outer circumference of the vessel with asbestos rope, clay and cow dung (mass of insulation) on the heat input and heat utilized by filling the vessel only with water at different levels; no food items are included. Therefore, heat utilized means the heat energy incurred for effective enthalpy rise of water and steam mixture. The same set of experiments is conducted on two popular brands of aluminum-based pressure vessels of similar capacity.

Results and discussion

Initially the body of the vessel (wall surface) is at atmospheric temperature of 30°C and the water is at 27°C only. During the first whistling point, the temperature and pressure of the steam are 116°C and 2.1 bar respectively. Certain amount of heat energy is absorbed by the vessel to reach the high temperature and maintain it. This quantity of heat energy is also included in heat loss. As the mass of water increases from a minimal value of 12.5% to 46% volume of the vessel, the heat energy required for evaporation increases and the heat energy utilized by the water also increases accordingly.

Time required for complete evaporation of water in the non-insulated and insulated vessels is given in Table 1. The data show that the vessel consumes almost the same time for evaporating 1 kg of water under both conditions. But the insulated vessel requires more time than the non-insulated vessel for evaporating 2, 3 and 3.7 kg of water. The heat balance for non-insulated and insulated pressure vessels for different masses of water in the vessels is enumerated in Table 2. Non-insulated vessel with water at 46% of its volume utilizes a maximum of 30% of heat energy supplied. When the outer circumference of the vessel is insulated, energy conservation is achieved only when the vessel contains water at 12.5% of its volume.

The whistling points are reached earlier in non-insulated vessel than insulated vessel (Figure 2). The number of whistling points is almost the same in both non-insulated and insulated cases. But the time of heat supply is more in the insulated vessel (Table 2). This additional heat supply is absorbed by the mass of insulation; thus the time between whistling points becomes more for insulated vessel. The heat energy absorbed by the mass of

Table 1. Time required for complete evaporation

Mass of water (kg)	Time taken for evaporation (sec)	
	Non-insulated vessel	Insulated vessel
1	2318	2315
2	4203	4576
3	6254	6916
3.7	7282	8114

Table 2. Heat balance data for the non-insulated and insulated conditions of the pressure vessel

Mass of water (kg)	Non-insulated vessel		Insulated vessel	
	Q_i (kJ)	Heat loss (%)	Q_i (kJ)	Heat loss (%)
1	5,057.19	84.13	5,050.87	80.31
2	9,170.80	76.95	9,983.92	76.90
3	13,644.32	74.44	15,089.30	73.66
3.7	15,887.87	69.36	17,690.00	71.01

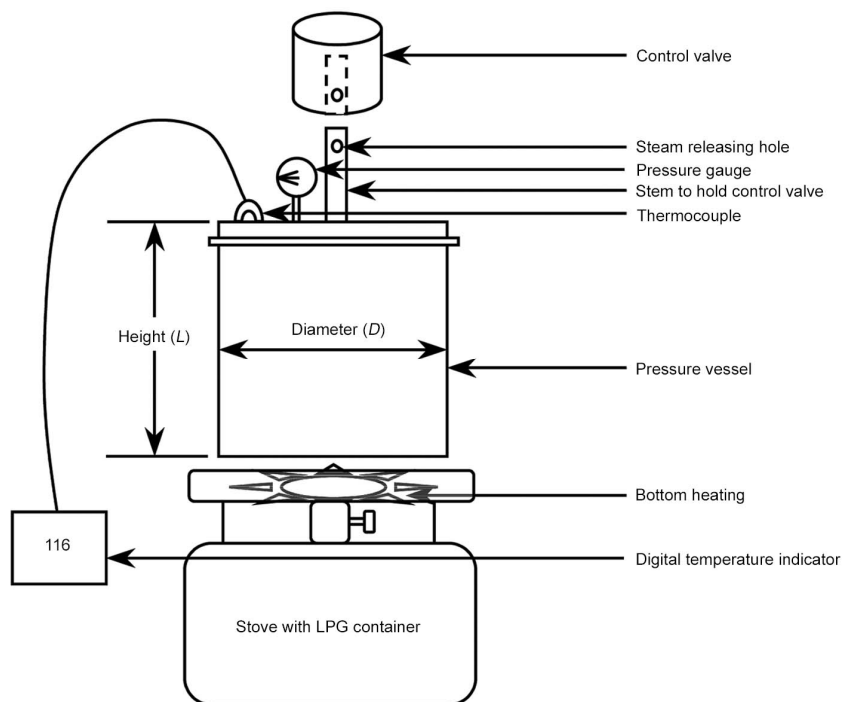


Figure 1. Schematic arrangement of the experimental set-up.

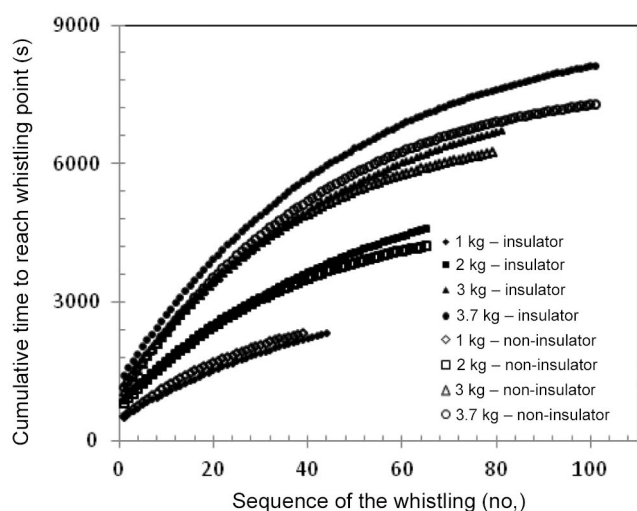


Figure 2. Cumulative time to reach whistling point for different water levels.

insulation detains high temperature of the vessel wall during the whistling time (steam release). Therefore, the time taken for reaching the whistling point (Figure 2) and whistling time to release the steam is more in insulated case (Figure 3). Since the temperature difference between ambience and vessel wall surface is remarkably high (150°C), wall temperature of the non-insulated vessel drops quicker and thus the whistling time is less than the insulated vessel. The deviation of whistling time and mass of steam released are significant for the case of 46% of water volume. Especially deviation increases with reducing levels of the contents.

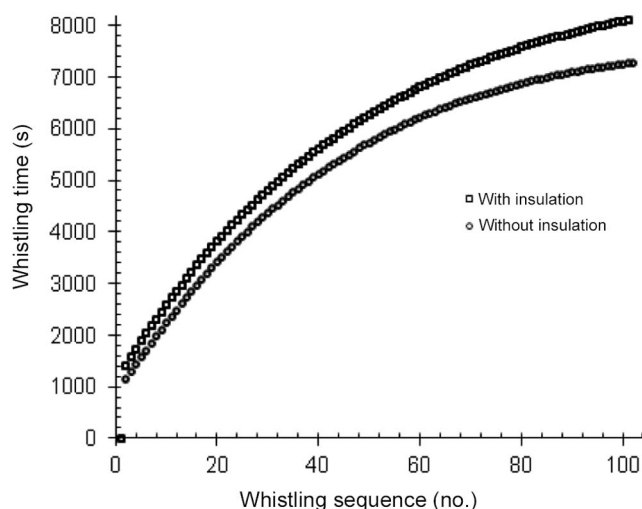


Figure 3. Whistling time of vessels with 3.7 kg water.

Heat input (Figure 4) and heat loss are less in the non-insulated case, which shows that the non-insulated vessel reaches the equilibrium state with its surroundings at a faster rate than the insulated vessel. In both insulated and non-insulated cases, the amount of heat energy required for complete evaporation of 1 kg of water from the vessel is almost the same. But the insulated vessel utilizes 20% of total heat input, while the non-insulated vessel utilizes only 16% of total heat input. Thus the heat loss is found to be more in the non-insulated vessel. This is due to large temperature difference between vessel wall surface and ambient air.

Heat energy utilized by the water is more in the insulated case (Figure 5) for different water levels considered for the experiment. This leads to two important points. One is that the insulated vessel consumes more time to reach the whistling point. The other is that the excess amount of heat utilization is stored in the mass of insulation. The method of insulation shows its effectiveness in a positive manner when 12.5% volume of the vessel is filled with water, i.e. when the 0.008 m^3 vessel is filled with 0.001 m^3 water. The heat energy saved is only around 6 kJ. Even though the heat input is observed to be approximately the same for both insulation and non-insulation cases, it is found that the heat energy utilization is increased by 4% in the case of insulation. The increase in energy utilization is to increase the temperature of the insulating medium. It can be inferred from Figure 5. Therefore the method of insulating the vessel does not help save energy.

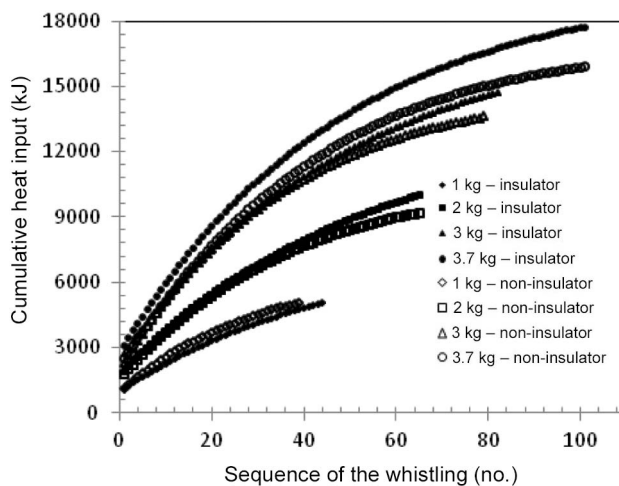


Figure 4. Cumulative heat input.

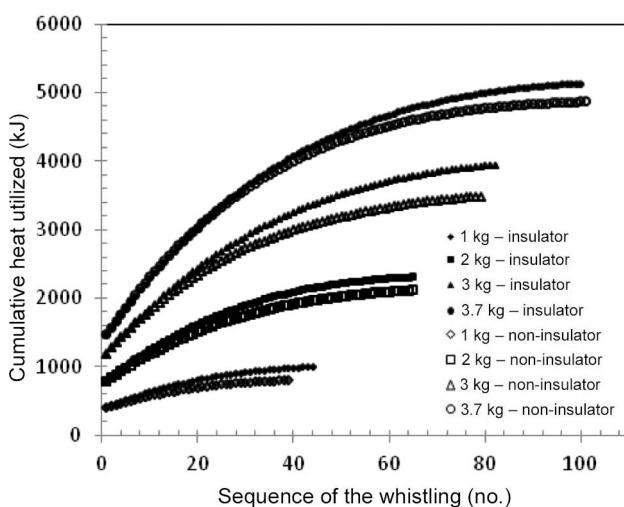


Figure 5. Cumulative heat utilized.

Mass of steam leaving the vessel is more during many of the whistling periods of the insulated vessel. The heat energy stored in the mass of insulation behaves like a high-temperature shield around the vessel wall and restricts reduction in temperature and pressure of the steam in the vessel during the whistling period. So the whistling time is more and the mass of steam leaving from the insulated vessel is also more. If the restriction is not offered by the mass of insulation like in the case of non-insulated vessel, the control valve sets down at a short period. Heat loss is more in the non-insulated case during the first 23 out of 64 whistling periods. Later more heat loss is observed in insulated vessel for 37.5% of volume filled with water. Finally total heat loss becomes reasonably high in the insulated vessel. Total heat transferred to the mass of insulation is greater than the heat transferred to air in the non-insulated vessel. This is also verified by the heat input and heat utilization curves, where the value of heat input and heat utilized is more during each whistling period for the insulated vessel.

For 46% volume of the vessel filled with water, the insulated vessel consumes more time as well as heat energy for developing the pressure and temperature of the steam to reach the whistling point in each whistling gap than the non-insulated vessel. The difference in time and heat energy consumption, between insulated and non-insulated vessels, was less for volume of water at 12.5%, 25% and 37.5% of vessel. But the mass of steam leaving the vessel during the whistling periods is more in non-insulated vessel during the first 26 out of 101 whistling periods. Later the mass flow rate of steam is more during the control valve lifting periods in the insulated vessel.

It is observed that while filling the 0.008 m^3 pressure vessel with 50% of its volume with water, i.e. 4 kg of water, the water particles escape through the control valve. This is because the volume available above the water surface in the vessel is not sufficient to develop the required pressure and temperature for generating the steam.

Normalized heat loss (ratio of heat loss during the complete evaporation of particular mass of water to the respective mass of water) is represented in Figure 6 for different volumes of water in the vessel. A smooth curve is obtained for insulated vessel, while an oblique curve is obtained for non-insulated vessel. This is because the mass of insulation behaves like a shield between the steam in the vessel and atmosphere; thus it controls heat dissipation to the ambient. It is understood that the mass of insulation acts like a heat reservoir, by absorbing heat energy during heating time and supplying part of the absorbed heat energy to the vessel during whistling period (control valve lifting period). But in the non-insulated vessel the heat energy dissipated to the ambient varies according to outside air temperature. Thus the insulated vessel is less sensitive and the non-insulated vessel is more sensitive with respect to heat loss. Optimum thickness of the insulation is applied on the outer

cylindrical surface of the vessel; the process of insulation helps increase the quality of steam by showing slightly higher dryness fraction value of the steam at a particular instant than the non-insulated vessel.

Heat balance characteristics of the vessel with reference to mass of water in the vessel

The heat balancing characteristics of the given vessel (Q_i , Q_u and Q_l (in kJ)) can be determined in terms of mass of water (m ; in kg) evaporated; equations are developed from the results obtained during the experiments for insulated and non-insulated vessels. In the case of non-insulated vessel, total heat input Q_i required for complete vapourization is as follows

$$Q_i = -343m^3 + 2238m^2 - 199.27m + 3361.5. \quad (6)$$

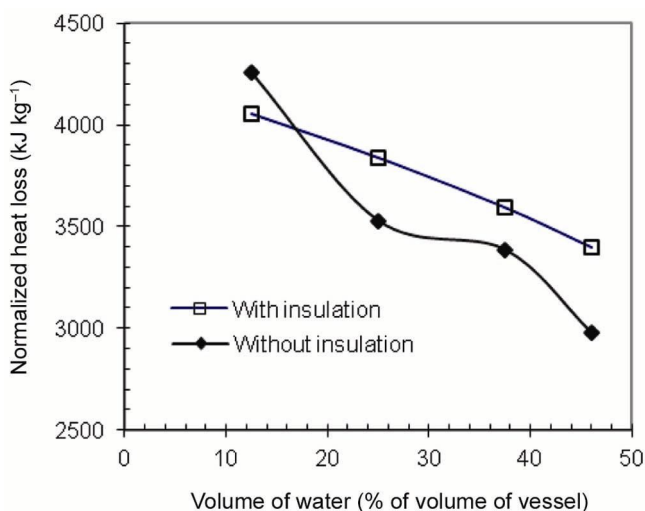


Figure 6. Comparison of normalized heat loss.

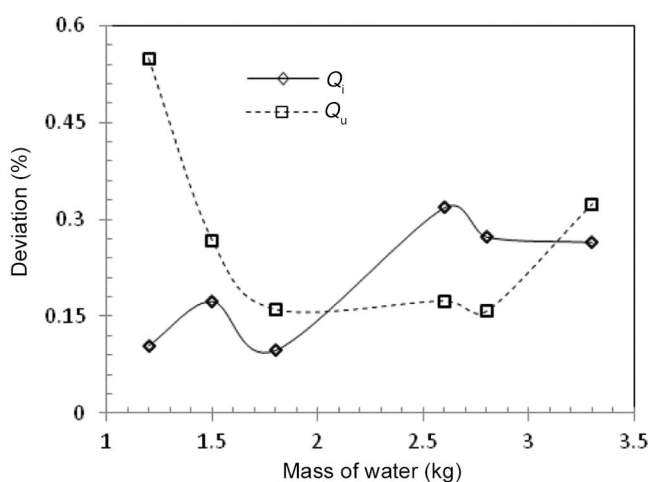


Figure 7. Percentage deviation of Q_i and Q_u from predicted values for the non-insulated vessel.

For insulated vessel, it is expressed as

$$Q_i = -34.78m^3 + 2094.8m^2 + 991.96m + 2298.8. \quad (7)$$

Total heat utilized (Q_u) by a non-insulated vessel for complete vapourization of water is

$$Q_u = 118.98m^3 - 682.76m^2 + 2526.9m - 1160.6. \quad (8)$$

In the case of insulated vessel total heat utilized (Q_u) is

$$Q_u = -70.85m^3 + 603.71m^2 - 3.569m + 465.42. \quad (9)$$

Total heat loss Q_l in a non-insulated vessel during complete vapourization of water is

$$Q_l = -461.98m^3 + 2920.7m^2 - 2726.2m + 4522.1. \quad (10)$$

For an insulated vessel total heat loss Q_l is

$$Q_l = -63.93m^3 + 1491.1m^2 + 995.53m + 1833.4. \quad (11)$$

Validation of heat balance equations in non-insulated pressure vessel

The experimental and prediction-based values of heat energy supplied and utilized for different masses of water are shown in Table 3. The predicted polynomial equation-based model yields better results for estimating the heat balance parameters Q_i , Q_u and Q_l in terms of mass of water used in the vessel.

Validation results show a maximum deviation of heat input (Q_i) as 0.32% for a water level of 2.6 kg and maximum deviation heat utilized (Q_u) as 0.55% for a water level of 1.2 kg (Figure 7), while considering the mass of water within the experimental mass limits (between 12.5% and 46% volume).

Validation of heat balance equations in insulated pressure vessel

Validation results show a maximum deviation of heat input (Q_i) as 0.06% for a water level of 3.3 kg and

Table 3. Validation data for heat input in a non-insulated vessel of volume 0.008 m³

Mass (kg)	Q_i		
	Experimental value (kJ)	Predicted value (kJ)	Deviation (%)
1.2	5,758	5,752	0.10
1.5	6,952	6,940	0.17
1.8	8,262	8,254	0.10
2.6	11,982	11,944	0.32
2.8	12,855	12,820	0.27
3.3	14,788	14,749	0.26

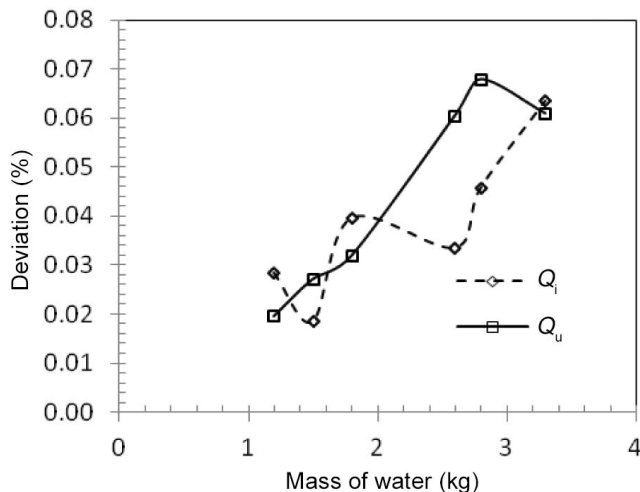


Figure 8. Percentage deviation of Q_i and Q_u from predicted values for the insulated vessel.

Table 4. Validation data for heat utilized in a non-insulated vessel of volume 0.008 m^3

Mass (kg)	Q_u		
	Experimental value (kJ)	Predicted value (kJ)	Deviation (%)
1.2	1,100	1,094	0.55
1.5	1,499	1,495	0.27
1.8	1,873	1,870	0.16
2.6	2,890	2,885	0.17
2.8	3,179	3,174	0.16
3.3	4,032	4,019	0.32

maximum deviation heat utilized (Q_u) as 0.07% for a water level of 2.8 kg (Figure 8 and Table 4), while considering the mass of water within the experimental mass limits (between 12.5% and 46% volume).

In both cases, the predicted equations are found to be convincing as the percentage deviations are too small. Since a minimum of 12.5% of the volume of the vessel will be filled with water and the vessel is unable to develop steam pressure beyond 46% of its volume, validation is not considered for those cases. Another important finding is that similar performance has been observed in both the popular brands of aluminum-based pressure vessels of the same capacity.

Conclusion

It is found that a huge amount of heat energy is lost to the atmosphere from a pressure vessel. Insulating the circumference of the pressure vessel becomes ineffective. Heat loss percentage decreases the increase in the contents of the pressure vessel. Heat loss includes the amount of heat energy required for raising and maintaining the vessel wall temperature and convection losses to the atmosphere. Heat energy utilized by the vessel increases with the contents of the vessel and reaches a maximum of 30% for non-insulated vessel with water at 46% of its volume. The heat balancing characteristics equations have been validated for non-insulated and insulated pressure vessels and were found effective within the experimental mass limits of water. Further studies are required on vessels of different capacity and diameter to height ratio. The utility of non-insulated vessel for shorter duration consumes less energy than insulated vessel of the same capacity. Development of steam pressure in the vessel is restricted beyond the limit of 46% of its volume filled with water. Two popular brands of aluminum-based pressure vessels of the same capacity were found to give similar performance.

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