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DESIGN OF A MOLTEN-LAVA, SINGLE-TUBE BOILER EXPERIMENT

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ABSTRACT

The design of the laboratory experiments which Sandia Laboratories will conduct to investigate many of the engineering problems associated with extracting energy from molten lava is described herein. Methods for interpreting the data from these experiments are also presented and discussed.

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DESIGN OF A MOLTEN-LAVA, SINGLE-TUBE BOILER EXPERIMENT

Introduction

The experiments with molten lava at Sandia Laboratories are designed to investigate many of the engineering problems associated with extracting energy from molten lava.¹ The purposes of these experiments and the information which we hope to obtain are as follows:

Determine the heat-extraction rate and compare with calculated values.

Determine the heat-transfer coefficient, h , and the thermal conductivity, K , of molten lava and compare them with previous measured values.

Check for departure from nucleate boiling (DNB) and compare with analytical predictions.

Determine the tube temperature during the tube-insertion transient and compare it with analytical predictions.

Determine the extent of the corrosion damage by molten lava to boiler tube materials.

Check the design of various tube heat exchangers.

Generate electricity from energy extracted from molten lava.

Experimental Apparatus

The experiment is designed so that it will be as safe as possible and at the same time procedurally simple. To achieve procedural simplicity the steam system will be "open loop," i. e., the steam will not be condensed and returned to the boiler but will be exhausted, and a vane turbine,² which can operate over varying load and input conditions and on low-quality steam, will drive a generator to produce electricity. The test apparatus will consist of a boiler on top of which the turbine and generator are mounted, a 165-kW inductive furnace, an external generator load, a boost pump-feedwater system, and a calorimeter-condenser system.

Boiler, Turbine-Generator, and Furnace

The boiler, turbine-generator, and furnace are shown schematically in Figure 1 and were photographed for Figure 2. The 165-kW furnace will be used to melt the lava and to supply sufficient heat during the tests to keep it in a molten state.

Figure 1. Schematic of Boiler, Turbine-Generator, and Furnace

Figure 2. Boiler, Turbine-Generator, and Furnace

The boiler and boiler tube were designed in Division 1543 with assistance from A. R. Hylton, 9613, and from P. P. Stirbis, 1544, who did the stress analyses. The boiler is constructed of one section of 24-inch schedule 20 steel pipe, two 24-inch steel ASME boiler end caps, and two 24-inch steel number 150 ASA flanges. The steam-separating baffle is a 20-inch steel ASME boiler end cap, and the boiler tube is a 61-cm (24-inch) segment of a 2-1/2 inch schedule 40, RA310 stainless steel (rolled alloy) pipe.

The ac generator is rated at 1-1/2 kW at 1750 rpm; the turbine is described in Reference 2. The relief valves are capable of bypassing 8.6 kg/min of steam at atmospheric pressure and, because of the increase in density of saturated steam with increased pressure, their capacity will increase as the boiler pressure increases.

The maximum steam-generation rate of the boiler can be found by assuming that all of the 165-kW output of the furnace is transferred to the water in the boiler tube. Then, based on the nominal value for the latent heat of steam of 555 cal/g, the maximum steam-generation rate is

$$\frac{165 \text{ kW}}{555 \frac{\text{cal}}{\text{g}} \times 10^3 \frac{\text{g}}{\text{kg}} \times 6.97 \times 10^{-5} \frac{\text{kW-min}}{\text{cal}}} = 4.3 \text{ kg/min} ,$$

which is less than the capacity of the relief valves. It is also unlikely that even half of the 165 kW will be transferred to the water in the boiler tube (because of radiation and cooling-coil losses, etc.) and, therefore, the bypass capacity of these valves is more than adequate to exhaust all the steam in case of turbine failure.

Another safety feature is the leveling valve to maintain the water level so the boiler is always at least 1/3 full. This amounts to 90 kg of water in the boiler, which would allow at least 15 minutes of safe operation after a booster pump failure.

The two turbine bypasses and the exhausts are manifolded and connected to the calorimeter-condenser system by a flexible hose so that system can be located some distance away from the boiler, thus steam quality and steam-generation rate may be safely measured during tests. Similarly, the leveling valve is connected to the boost-pump/feedwater system by a flexible hose.

The boiler will be suspended by an overhead crane so the boiler tube can be positioned and lowered into the molten lava. After the boiler tube is in the lava, nucleate boiling will produce steam. (However, several minutes will pass before steam will leave the boiler because, until all the water in the boiler is raised to the saturation temperature, the steam will condense before it rises above the water.) After the water reaches saturation temperature, steam will rise and impinge on the baffle at the top of the boiler where any entrained water droplets will be separated from the steam, and saturated steam will leave the boiler above the baffle. Valves are so placed that the steam to the turbine can be shut off to permit the boiler to be pressurized to the pressure ratings of the relief valves.

External Generator Load

The external generator load consists of five flood lamps, in the array shown in Figure 3, located a safe distance away from the boiler so the switches can be thrown off and on during the tests to vary the load. The output current and voltage are monitored by an ammeter and voltmeter.

External Boost Pump-Feedwater System

The boost pump-feedwater system is so designed that the pump runs continuously, thus the need for a complex switching system is eliminated. A schematic of this system is Figure 4 and the actual hardware was photographed for Figure 5.

Legend: L Denotes Lamp
SW Denotes Toggle Switch

Figure 3. Schematic of External Generator Load

Figure 4. Schematic of Boost Pump-Feedwater System

Figure 5. Boost Pump-Feedwater and Calorimeter-Condenser Systems

The boost pump is an Oberdorfer Model HRP-1 helical rotor pump which is driven at 1725 rpm by a 3/4-hp, capacitor-start electrical motor. At 1725 rpm the pump's capacity is 14 kg/min, which is greater than the maximum steam-generation rate of 4.3 kg/min by an adequate margin.

The relief valve will permit the feedwater to recirculate through the pump when the leveling valve is closed. By measuring the water level in the barrel, the steam-generation rate of the boiler can be determined and compared with the steam rate measured by the calorimeter/condenser system.

Calorimeter-Condenser System

The calorimeter-condenser system is shown schematically in Figure 6, and the actual hardware can be seen in Figure 5. The calorimeter consists of two pressure gages, a gate valve to throttle the steam, and a thermometer. The quality of the steam will be determined from this apparatus by the principles of throttling calorimetry.

Figure 6. Schematic of Calorimeter/Condenser System

The condenser system consists of two barrels of water, into which the steam will be condensed and weighed to determine the steam rate of the boiler. Ball valves are placed in the lines as shown so that the steam from the boiler can either be condensed or exhausted outside the building.

Test Plan

The tests which follow are designed to answer the purposes outlined in the introduction.

First Test Run

The purposes of this test are to determine the steam quality, heat-extraction, the heat-transfer coefficient h , and the effective thermal conductivity K of magma. The boiler pressure will be maintained at atmospheric pressure by removing the vanes from the turbine so the steam, as it leaves the boiler, will be essentially unrestricted. With the furnace on, the boiler tube will then be lowered into the molten lava and, after the steam-generation rate has stabilized, the steam generation rate and steam quality will be measured with the condenser and calorimeter. The furnace will then be turned off, and the quality and steam-generation rate will be measured as the generation rate decays. The effective thermal conductivity can then be found by the calculations described under "Experimental Techniques and Analytical Predictions."

Second Test Run

This test will be identical to the first test run except the boiler pressure will be maintained at the rated pressure of the relief valves by closing the inlet valves to the turbine.

Third Test Run

The turbine vanes will be replaced, and the turbine will be run to produce electricity. Although the generation of electricity is more political than technical in value, some additional technical information can be obtained from this test. The external generator load can be used to control the pressure in the boiler and thus the steam-generation rate, the quality of the steam, and the thermal conductivity of the lava can be determined at boiler pressures other than atmospheric and at the rated pressure of the relief valves.

Fourth Test Run

A long-duration run (about 100 hours) to determine the corrosive effect of molten lava on tube materials will be made. For this test the vanes will be removed from the turbine so the boiler pressure will be atmospheric, eliminating the hazards associated with exhausting high-pressure steam for a long period of time.

Experimental Techniques and Analytical Predictions

Although some of the experimental techniques which will be used have been mentioned in previous sections, a more detailed discussion of these techniques is given in this section along with the analytical expressions, which are necessary to analyze the experimental data, and the analytical predictions, which are the bases for comparison of these experiments.

Heat-Extraction Rate

The heat-extraction rate, which is the energy-extraction rate from the lava, will be determined in three ways:

By determining the steam-generation rate;

By measuring, before any steam is produced, the temperature rise of the water in the boiler; and

By measuring the pressure rise in the boiler after the calorimeter valve is closed.

Steam-Generation Rate -- The heat q is given by

$$q = \dot{m} \Delta h , \quad (1)$$

where $\dot{m}$ is the steam-generation rate, i. e., the mass of steam which is generated in the boiler per unit time, and Δh is the enthalpy of the steam leaving the boiler less the enthalpy of saturated water at the boiler pressure. The enthalpy difference Δh is given by

$$\Delta h = X h_{fg} , \quad (2)$$

where X is the quality of the steam leaving the boiler (measured in the calorimeter) and h_{fg} is the latent heat of the steam at the boiler pressure. The steam-generation rate will be determined by weighing the increase in weight m of the water in the condensers during the time τ , and/or by measuring the change in the feedwater level ΔY in the feedwater barrel over the time τ' . Then

$$\dot{m} = \frac{m}{\tau} , \quad (3)$$

and/or

$$\dot{m} = \frac{\pi r_i^2 \Delta Y}{\tau'} \rho_w , \quad (4)$$

where ρ_w is the density of the feedwater, and r_i is the inner radius of the condensing barrel. These measurements will be made, of course, after the steam-generation rate has stabilized.

Temperature Rise of Water in Boiler -- By placing a thermocouple on the outside of the lower portion of the boiler, the temperature rise of the water in the boiler (before any production of steam) can be measured and recorded with time. Then

$$q = \frac{\rho_w V \Delta T}{\tau} \times 1 \text{ cal/g } ^\circ\text{C} , \quad (5)$$

where $V = 0.084 \text{ m}^3$ is the volume of water in the boiler, and ΔT is the temperature rise of the boiler during the time τ .

Boiler Pressure Rise During Pressurization -- The heat-extraction rate required to pressurize the boiler is given by

$$q = \rho_w V \Delta u \quad (6)$$

where Δu is the change in the internal energy of the water-steam mixture as the pressure increases. Since for a constant volume process $\Delta u = h_2 - h_1 - v(p_2 - p_1)$, where v is the specific volume of the water-steam mixture and $(p_2 - p_1)$ is the change in pressure, Equation (6) can be written for a constant volume process as

$$q = \rho_w V [h_2 - h_1 - v(p_2 - p_1)] \quad (7)$$

States 1 and 2 correspond to the thermodynamic states before and after pressurization, respectively; the specific volume v is constant, and since the boiler is so designed that, initially, 1/3 of its volume is filled with water,

$$v = \frac{3V}{\rho_w V} = \frac{3}{\rho_w} \quad (8)$$

From steam tables at p_1 , v_{f1} , v_{fg} , h_{f1} , and h_{fg1} can be found, where v_{f1} is the specific volume of saturated water at p_1 , v_{fg} is the change of the specific volume of water during vaporization at p_1 , h_{f1} is the specific enthalpy of saturated water at p_1 , and h_{fg1} is the latent heat of water at p_1 . Then the quality X_1 of the water-steam mixture can be computed from

$$X_1 = \frac{v - v_{f1}}{v_{fg1}} \quad ,$$

and the enthalpy of the mixture at state 1 is

$$h_1 = h_{f1} + X_1 h_{fg1} \quad (9)$$

Similarly, the quality of mixture at state 2 is given by

$$X_2 = \frac{v - v_{f2}}{v_{fg2}} \quad ,$$

and the enthalpy of the mixture at the end of the pressurization is given by

$$h_2 = h_{f2} + X_2 h_{fg2} \quad (10)$$

Heat-Transfer Coefficient and Thermal Conductivity

The heat-transfer mechanism in the lava may be either conduction or convection dominated. If it is conduction dominated, the steady-state conduction through the magma is given by the equation for the conduction through concentric cylinders, which is³

$$q = \frac{2\pi KL (T_2 - T_1)}{\ln r_2/r_1} \quad (11)$$

where K is the thermal conductivity of the magma, L is the effective heat-transfer length of the tube, T_1 is the crucible wall temperature, r_1 is the outer radius of the boiler tube, and r_2 is the inner radius of the crucible. Since the boiler-tube temperature will be very near the saturation temperature of the steam in the boiler, we can assume that $T_1 = 100^\circ\text{C}$ (the saturation temperature of the steam at atmospheric pressure). Then since r_1 and r_2 are fixed at 2.50 and 14.1 cm, respectively, the maximum heat transfer by conduction depends on the maximum allowable temperature of the crucible wall and the maximum effective heat-transfer length of the tube. For metallurgical reasons, the maximum allowable temperature of the graphite walls of the crucible is 1650°C , and the maximum effective heat-transfer length is the crucible depth (38.1 cm). K is given in Reference 4 as $0.007 \text{ cal/cm-s-}^\circ\text{C}$. Then from Equation (11) the maximum heat transfer possible in the lava by conduction is

$$q = 2\pi \times 0.007 \frac{\text{cal}}{\text{cm-s-}^\circ\text{C}} \times 418.4 \frac{\text{W}}{\frac{\text{m-}^\circ\text{K}}{\frac{\text{cal}}{\text{cm-s-}^\circ\text{C}}}} \times 38.1 \text{ cm}$$

$$\times \frac{(1650 - 100)^\circ\text{K} \times \frac{\text{x}}{100} \frac{\text{m}}{\text{cm}} \times \frac{1}{1000} \frac{\text{kW}}{\text{W}}}{\ln \frac{14.1}{2.54}}$$

or

$$q = 6.3 \text{ kW}$$

Thus, unless the effective conductivity of the lava is significantly larger than $0.007 \text{ cal/cm-s-}^\circ\text{C}$, the conduction-dominated heat rate is limited to 6.3 kW and, since about 0.645 kWh is required to vaporize 1 kg of water, the maximum steam-generation rate possible with conduction-dominated heat transfer is 0.164 kg/min.

For convection-dominated heat transfer

$$h = \frac{q}{A(T_L - T_1)} \quad (12)$$

where h is the convective heat-transfer coefficient, A is the effective outer heat-transfer area of the tube, and T_L is the ambient lava temperature. The temperatures T_1 and T_L will be measured by thermocouples and q will be determined by the method described under "Heat-Extraction Rate."

The thermocouple measurements of the ambient lava temperature T_L will be made in two ways: (1) by lowering into the lava a thermocouple attached to the end of a boom, and (2) by a thermocouple rake attached to the boiler tube as shown in Figure 7. From these temperature measurements the temperature profile in the lava can be determined.

Figure 7. Location of Thermocouples on the Boiler Tube

Figure 8 shows typical temperature profiles for both conduction- and convection-dominated processes and, as can be seen, they are radically different. The conduction profile is logarithmic while the convection curve consists of two boundary layers--one near the boiler tube and one near the crucible wall. By comparing the shape of the lava-temperature profile measured by the thermocouple rake to these typical profiles, the nature of the heat transfer in the lava may be inferred.

Figure 8. Typical Conduction and Convection Temperature Profiles

For conduction-dominated heat transfer, the conductivity can be determined from Equation (11) by substituting r for r_2 and T for T_2 to obtain

$$K = \frac{q \ln \frac{r}{r_1}}{2\pi L(T - T_1)} \quad , \quad (13)$$

where T is the measured temperature at the radius r .

For a convection-dominated process, the effective thermal conductivity of the lava can be estimated by measuring the temperature within one of the boundary layers; in general, this is difficult to do because of their thinness. However, if at least one of the thermocouples in the rake shown in Figure 8 is inside the boundary layer on the tube, the conductivity can be estimated from Equation (13) by substituting for T the temperature measured by the thermocouple nearest the tube and for r the radial position of this thermocouple.

Departure from Nucleate Boiling (DNB)

From Figure 10.4 in Reference 3, DNB for boiling water is

$$q/A = 5 \times 10^5 \frac{\text{Btu}}{\text{hr-ft}^2} \quad .$$

Hence, DNB in the tube will occur when the heat rate reaches

$$q = 2\pi \times 1 \text{ in.} \times \frac{1 \text{ ft}}{12 \text{ in.}} \times 1.25 \text{ ft} \times 5 \times 10^5 \frac{\text{Btu}}{\text{hr ft}^2} \times \frac{1}{3413} \frac{\text{kW}}{\text{Btu/hr}} = 96 \text{ kW} .$$

Therefore, if all of the 165-kW capacity of the furnace is transferred to the tube, DNB will occur. However, because of radiation and cooling-coil losses, etc., the heat transferred to the tube will probably not approach 96 kW, and the boiling in the tube will remain nucleate.

DNB can be detected in the experiment, if it exists, by a sudden increase in tube temperature and a sudden decrease in the boiler pressure, in which case the furnace will immediately be shut off and the boiler tube will be raised from the crucible.

Tube Temperature During the Insertion Transient

The temperature transient in the tube during insertion will be measured by thermocouples placed on the tube as shown in Figure 8. The tube temperature during the tube-insertion transient can also be predicted. Initially, the steel tube at temperature T_s and lava at temperature T_L can be treated as semi-infinite slabs, and the heat transfer in the lava will be conduction dominated. Then a solution in Carslaw and Jaeger⁴ for the instantaneous contact of semi-infinite slabs can be used to obtain, for short times,

$$\frac{T - T_s}{T_L - T_s} = \frac{\sqrt{(K\rho c)_L}}{\sqrt{(K\rho c)_s} + \sqrt{(K\rho c)_L}} , \quad (14)$$

where T is the temperature at the stainless steel tube/lava interface, T_s is the initial temperature of the tube, T_L is the ambient temperature of the lava, ρ is the density, K is the conductivity, and c is the specific heat. Subscripts L and s denote lava and stainless steel, respectively.

Equation (14) can also be written as

$$\frac{T - T_s}{T_L - T_s} = \frac{1}{1 + \sqrt{\frac{K_s}{K_L}} \sqrt{\frac{(\rho c)_s}{(\rho c)_L}}} , \quad (15)$$

where $(\rho c)_L$ does not include the effects of a phase change in the lava. Since the initial tube temperature is less than the melt temperature of the lava, the lava will solidify on the tube

surface. This means that Equation (15) must be modified to include this phase change. The change of the internal energy of the lava, including phase change, may be written as

$$\Delta u = \bar{c} (T_L - T_S) = c_L (T_L - T_f) + \mathcal{L} + c_s (T_f - T_S) \quad (16)$$

where Δu is the change in the internal energy per unit mass of lava which is solidified, $\bar{c}$ is the effective specific heat of the lava, c_L is the specific heat of liquid lava, T_f is the melt temperature of lava, $\mathcal{L}$ is the latent heat of lava, and c_s is the specific heat of solidified lava. Then if $c_L \approx c_s = c_L$, Equation (16) can be solved for $\bar{c}$ to give

$$\bar{c} = c_L + \frac{\mathcal{L}}{T_L - T_S} \quad (17)$$

If the densities of solid and liquid lava are assumed equal,

$$\frac{(\rho c)_s}{(\rho c)_L} = \frac{\frac{(\rho c)_s}{(\rho c)_L}}{1 + \frac{\mathcal{L}}{c_L (T_L - T_S)}} \quad (18)$$

and Equation (15) can be modified to include phase change by substituting Equation (18) into Equation (15) for $\frac{(\rho c)_s}{(\rho c)_L}$ to obtain

$$\frac{T - T_S}{T_L - T_S} = \frac{1}{1 + \sqrt{\frac{(\rho c K)_s}{(\rho c K)_L}} \sqrt{\frac{1}{1 + \frac{\mathcal{L}}{c_L (T_L - T_S)}}}} \quad (19)$$

Equation (19) predicts the maximum temperature which the tube will reach during the temperature transit. The tube temperature will then decrease and reach a steady-state value which will be much less than the maximum temperature.

The lava temperature is expected to be of the order of 1200°C, T_s will be essentially room temperature, say 21°C, and the properties of the stainless steel and lava are as follows:

$$\text{Lava}^5: \rho = 2.7 \times 1000 \frac{\text{kg}}{\text{m}^3} = 2700 \frac{\text{kg}}{\text{m}^3}$$

$$c = 0.25 \text{ cal/g-}^\circ\text{C}$$

$$L = 100 \text{ cal/g}$$

$$K = 0.007 \text{ cal/cm-s-}^\circ\text{C}$$

$$\text{Stainless Steel}^3: \rho = 7834 \frac{\text{kg}}{\text{m}^3}$$

$$K = 0.0306 \text{ cal/cm-s-}^\circ\text{C}$$

$$c = 0.11 \text{ cal/g-}^\circ\text{C}$$

Then from Equation (19), the maximum tube temperature is

$$\frac{T - 21}{1200 - 21} = \frac{1}{1 + \sqrt{\frac{(7834)(0.11)(0.0306)}{(2700)(0.25)(0.007)}} \sqrt{1 + \frac{1}{0.25(1200 - 21)}}},$$

or $T = 427^\circ\text{C}$.

P. P. Stirbis, 1544, has studied the thermal stresses in the tube associated with the sudden temperature change; his analysis and results are included in the Appendix.

Corrosive Effects of Molten Lava

The corrosive character of molten lava will be studied by M. J. Davis, 5830, and will therefore not be discussed in this report.

Design of Various Heat Exchangers

We would like to vary the design of the tube to determine if a forced circulation inside the tube would enhance heat transfer and create more uniform boiling inside the tube, i.e., insure that the entire boiling is nucleate and not film. This would entail concentric tubes and a circulating-pump/control system.

APPENDIX

Thermal Stress Analysis for the Boiler Tube

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February 21, 1974

Object

The object of this analysis was to determine the thermal stress distribution in the pipe used for the molten lava tap. The pipe is a 2.5-inch schedule 40, with a 2.875-inch outside diameter and a 2.469-inch inside diameter.

The pipe is assumed to be at 70° initially before it is immersed into molten lava. The outside surface will then increase to about 1100°F.

Method of Solution

The finite element computer program SASL was used to determine the stress response to the thermal gradient. The gradient is shown in Figure A-1.

Figure A-1. Thermal Gradient

The material used for the pipe is 310 stainless steel, with the following properties:

$$E = 29 \times 10^6 \text{ psi}$$

$$\alpha = 8.5 \times 10^{-6} \text{ in./in./}^\circ\text{F}$$

$$\gamma = 0.3$$

$$\text{Tensile yield} = 45,000 \text{ psi}$$

$$\text{Tensile ultimate} = 95,000 \text{ psi}$$

$$e = 45\%$$

The ambient stress/strain curve used in the analysis is shown in Figure A-2. The finite element mesh model is shown in Figure A-3.

The maximum tensile strain is at the inside surface and is 0.004 in./in. This is beyond the elastic yield strain of 0.0015 in./in. (see Figure A-2) but still well below the ultimate strain capability of 0.45 (45%).

Figure A-2. Stress/Strain Curve used in Model

PIPE FOR MOLTEN LAVA TAP

Figure A-3. Finite Element Mesh Model

Conclusions

The pipe for the molten lava tap may develop plastic strains due to the initial 1100°F outside surface temperature, but it will be only a local effect confined to the inside surface. Rupture will not occur. When the outside surface cools, the inside surface will go into a state of residual compression which will actually increase its strength for the next thermal cycle.

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