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Surrogate Fluid Selection for Space Rankine Cycle Start-up Experiment Testing

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SURROGATE FLUID SELECTION FOR SPACE RANKINE CYCLE START-UP EXPERIMENT TESTING

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ABSTRACT

This report discusses the start-up and associated control requirements of the potassium Rankine system selected as part of Phase I of the National Aeronautics and Space Administration (NASA) NRA for the development of a liquid-metal Rankine power conversion system for use with multiple power sources. The purpose of this report is to identify the experiments that need to be performed and propose fluids with which to perform the experiments. The Rankine cycle system design selected incorporates a separate start-up loop to execute the start-up process from the frozen state. An experimental plan to demonstrate the feasibility of the possible control strategy for the start-up process is outlined, and the basis for selecting the surrogate fluids for those experiments is given. The experiments related to start-up of a Rankine system that will be most beneficial for operation in microgravity are related to (1) demonstrating component configurations that are not susceptible to damage during the freezing and thawing of the working fluid, (2) demonstrating the ability to minimize the number of active components in the system by starting the system with a minimum number of control valves, and (3) the ability to control working fluid inventory during the freeze process and during low-power (and flow) conditions such as those that occur during cycle start-up and shutdown. Paraffin wax is proposed as a surrogate fluid to test the ability to freeze and thaw in the system without having to cool the system below room temperature. These tests are precursors to more definitive testing using potassium to assess individual component resistance to damage due to the freeze and thaw process. FC-72 would be used for experiments in which testing is to occur only in the liquid and gas phases. Cyclohexane is proposed for more elaborate experiments that would range in temperature from below the freezing point to the boiling point of the fluid, allowing tests to be conducted from the frozen state to operating conditions that simulate normal full-power operation. A condenser design that permits operation of the start loop with appropriate inventory control and that allows seamless operation with the main condenser over all vapor flow rates must be developed prior to the execution of several of these start loop tests.

1. INTRODUCTION

This report discusses the start-up and control requirements of the potassium Rankine system selected as part of Phase I of the National Aeronautics and Space Administration (NASA) NRA for the development of a liquid-metal Rankine power conversion system for use with multiple power sources.[1] An experimental plan to demonstrate the feasibility of possible control strategies is outlined, and the basis for selecting the surrogate fluids for those experiments is given.

The baseline design for this system was defined in Phase I of the program to be a two-loop system in which a common reactor coolant loop (including the primary side of the boiler) feeds two redundant power conversion loops. A schematic of the baseline design is shown in Fig. 1 with only one of the two secondary systems represented. The heat produced in the lithium-cooled reactor is transferred across a boiler where potassium vapor is produced. The potassium passes through a turbine that turns a generator. In the baseline design the exhaust passing through the turbine is passed directly to the condenser-radiator system, and no waste heat recovery is attempted. The liquid exiting the condenser is pumped by the main turbine-driven boiler feed pump and returned to the boiler. A portion of the vapor produced in the boiler is passed through the turbine driven boiler feed pump to circulate the potassium through the system. These basic features of the system must be supplemented with components to facilitate control and perform safety functions. Additional components may be required to accommodate both the initial start-up as well as shutdowns and restarts that occur in deep space, which is a programmatic requirement for this project. It is desirable that the number of additional components be minimized to simplify operation and increase reliability. The components required depend upon the baseline start-up system design and the selected modes of operation. The addition of each component is a trade among the operational flexibility afforded, the increased mass, and the impact on system reliability.

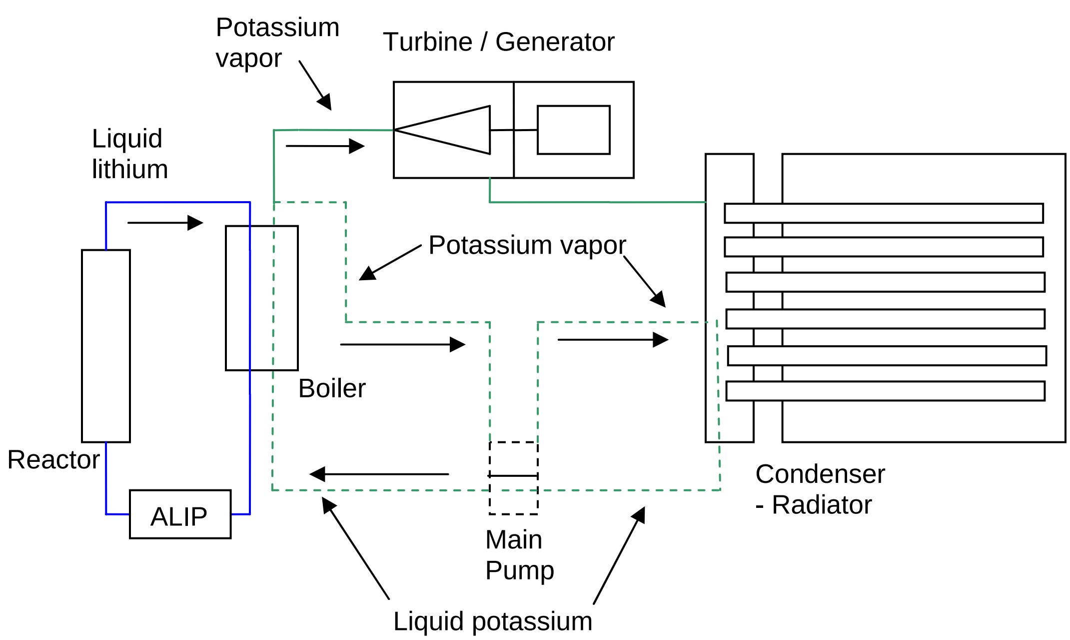

Fig. 1. Schematic showing baseline components of a lithium-cooled reactor and a boiling potassium secondary system (one of two redundant PCSs shown).

A deep space restart assumes that solar power is too weak to be of assistance in the restart process. Consideration must also be given to the time delay in communicating with the system from Earth. The system will have to shut down without operator intervention and restart with minimal operator instruction. Restart will also have to occur with limited onboard auxiliary energy. Onboard power is assumed to come from a Radioisotope Thermoelectric Generator (RTG). The implication of this assumption is that the supply of energy is essentially infinite compared to the restart duration, but it is delivered at a fairly low rate of approximately 125 W(e) (the anticipated capacity of the next-generation multimission RTG currently under development). Batteries could be used; however, they represent a potential reliability concern for missions of 10 to 15 years, and it would be preferable to avoid reliance on them if possible.

2. START-UP ISSUES: TEMPERATURE DISTRIBUTION, THAWING OF THE WORKING FLUID, FLOW INITIATION, AND INVENTORY MANAGEMENT

2.1 TEMPERATURE DISTRIBUTION

During the start-up sequence, heat from the reactor is transferred by flowing lithium to the boiler. The outer shell of the boiler is warmed to essentially the lithium temperature, and the secondary system is warmed by conduction through the boiler tubes and by radiation to components that share a view factor with the boiler. It may be possible for the entire secondary system to be warmed above the melting point of the potassium, but it is only necessary to warm a continuous loop from the boiler, through the turbine side of the boiler feed turbopump, through a condenser (either a condenser dedicated to start-up or a portion of the main cycle condenser), back through the liquid side of the main potassium pump, through a thermoelectric electromagnetic (TEM) pump (if one is incorporated on the secondary system), and back into the boiler. Those components represent the start loop for the system, and they form a path represented in Fig. 1 by dashed lines.

The start-up strategy proposed is to initiate flow through the start loop at such a rate that the main turbine-driven pump can begin to operate. As the power to the pump is increased, the flow rate through the boiler can be increased, and the reactor power can be stepped up to successively higher levels. Vapor in excess of that required to operate the pump would be used to spin up the main turbine, and the initial electrical power produced would be used to power the reactor annular linear induction pump (ALIP), allowing further increases in reactor power.

Thermal conduction alone may not be sufficient to warm the start loop to operating temperatures. A heat shroud may be used to enclose the start loop components so that radiant heat from the primary system can thaw the start loop. It is also possible to run heat pipes from the boiler to selected critical locations where conduction or radiation are not sufficient. Using various combinations of the available techniques, it is probable that an adequate temperature distribution can be established for start-up to proceed without the use of trace electrical heaters. The more difficult aspect of start loop operation appears to be assuring that inventory is properly managed within the system to safely shut down and restart the start loop. The system must be shut down in a manner that places the inventory in locations that (1) will not damage components and (2) will allow the system to restart.

It has been proposed to line the inner surfaces of the piping within the start loop with a thin layer capillary structure to supplement the thawing of the system and ensure liquid inventory in the proper locations. The capillary structure will always be filled with the working fluid due to capillary forces. Heat radiated from the shroud would be conducted through the wall of a pipe, pass through the wick structure, and initiate the melting and vaporization processes. Vapor will travel toward colder regions of the loop and condense. Capillary forces will draw new liquid to the hottest spots on the inner surface of the pipes, creating areas of localized working fluid circulation similar to the circulation in a heat pipe. The temperature difference between surfaces receiving radiant heat and surfaces receiving heat from the circulating fluid will be minimized, and the process should not require excessive power consumption or result in large temperature gradients. The potential drawback of the proposed approach is an increased pressure drop through the transport pipes during normal operation; however, this can be accommodated by increasing the pipe diameter or pump capacity.

2.2 BOILER ISOLATION AND MAIN PUMP ROTATION

If potassium vapor is being generated in the boiler and the boiler outlet is open to the remainder of the power conversion system (PCS), then working fluid will be transferred to and deposited on cooler surfaces in the system. If a method does not exist to return the working fluid to the boiler through the start loop, the inventory will boil away and may not be recoverable. If the inventory in the boiler is exhausted, the system may be in a state from which it cannot be restarted. The components that have the greatest potential for accumulating inventory are the turbine and the condenser.

If energy from the reactor is used to heat the secondary system through the boiler, then the boiler temperature will determine the temperature distribution throughout the start loop. To increase the start loop temperature, the boiler temperature must be increased. If working fluid is in the boiler, then the temperature of the boiler is limited to the saturation temperature of that fluid, and the pressure in the boiler must be increased to increase the saturation temperature.

There are two possible operating scenarios at this point. If the boiler is empty, it can be heated to a predetermined temperature, and liquid can be forced into the boiler where it will vaporize immediately. If the boiler has liquid potassium in it and it can be isolated, its temperature can be increased by isolating it and allowing the pressure to increase. However it is produced, the vapor in the boiler must first be used to initiate rotation of the main pump. Two possibilities have been considered for how this could occur.

If a valve is used to isolate the vapor inlet of the boiler feed turbopump, then the system can be started by isolating the boiler from the main turbine and the pump and at the boiler inlet, increasing the temperature and pressure in the boiler (which also warms the start loop components) and opening the pump isolation valve once the temperatures and pressure differential are sufficient to initiate boiler feed pump rotation. This fast start option, however, would almost certainly require careful control of the boiler inlet flow rate and would probably represent a significant transient to the system.

If an isolation valve is not used between the boiler feed pump turbine inlet and the boiler outlet, then the vapor inlet line to the pump could be allowed to fill with liquid as the system warms and begins to produce vapor. Flow through the start loop would be induced by a thermoelectric electromagnetic (TEM) pump. Vapor would form in the boiler and initially condense in the line leading to the boiler feed pump turbine. Eventually the system would be hot enough and the volume occupied by the vapor large enough for the vapor to expand through the boiler feed pump turbine and into the condenser. The vapor flow rate would be gradually increased until it was sufficient to turn the main pump. This start-up option would take considerably longer to complete and would probably have unstable chugging flow at times that could cause vibrations throughout the system; however, it would produce less severe transients in the system than would the fast start option.

2.3 CONNECTION TO THE CONDENSER AND INVENTORY MANAGEMENT

The turbine exhaust exits into the condenser during normal operation, and the condenser inlet is designed to handle the full-power potassium vapor flow of approximately 270 g/s. The vapor flow that drives the boiler feed pump turbine could enter the condenser at this same location. However, if it did, then (1) the entire condenser would have to be increased to operating temperature for start-up and (2) the entire condenser inventory would have to be pumped during the initial start-up phases.

Another possibility is to drain the condenser prior to restart and use the vapor from the boiler to gradually fill the condenser as start-up progresses. This is acceptable only if the inventory can be prevented from simply condensing onto surfaces that will preclude it from being pulled back into the flowing loop.

A condenser arrangement would be required that allows the vapor used to drive the boiler feed pump turbine to be condensed and reused within the start loop (it cannot be allowed to flow back through the system). Also, the design needs to be such that fluid not utilized in the start loop can remain solid (possibly within the condenser to prevent backstreaming) without interfering with start-up. Any solid potassium within the condenser will eventually thaw and must do so without causing damage. Vapor in excess of what the start loop can accommodate would be dumped into the main inlet of the condenser, and it must be possible for that portion of the fluid to flow through the condenser and be retuned to the boiler. Therefore the condenser has the conflicting requirements that (1) the start loop vapor must be prevented from backstreaming by a solid block of working fluid and (2) excess vapor cannot accumulate above the blockage, causing the condenser to overfill.

It was noted in the Medium Power Reactor Experiment (MPRE) that a jet of vapor was required near the condenser tube outlets to assist in pulling liquid inventory through the system[2] at full power. The vapor used to drive the boiler feed pump turbine could potentially be routed to enter the condenser at a location near the main condenser exit to perform this scavenging function after it has been condensed in a separate condenser.

3. SUPPLEMENTAL COMPONENTS AND OPERATING STRATEGY

3.1 TEM PUMP

During the start-up sequence the system will warm and eventually begin to form vapor. Any vapor initially formed in the boiler will pressurize the system and migrate to cooler surfaces and condense. Pumping will be required to establish flow in the system to replace vapor lost from the boiler due to evaporation. Pumping can be induced by battery-powered electrical pumps or by TEM pumps. A secondary-side TEM pump is assumed for this system because it does not require batteries to operate. With TEM pumps on both the reactor and secondary-sides, liquid metals will inherently begin to flow as system temperatures increase.

The primary TEM pump must be sized to maintain adequate flow rates to remove the heat generated in the reactor during that period of operation prior to the rotation of the turbine and the availability of electrical power to operate the primary-side ALIP. The secondary TEM pump must be sized to provide enough feed flow into the boiler to match the vapor flow rate required to initiate rotation of the main potassium boiler feed pump. There is little reason to doubt that the TEM pumps can operate as desired; however, the integration strategy of the units into the system and their masses have yet to be determined.

3.2 BYPASS SYSTEM

The two-loop system can be operated with (1) a single unit operating, (2) two units operating with one unit operating at low power in standby or idle mode, or (3) with both units sharing the load. The advantage of keeping one system shut down is that unanticipated failure modes would occur only in the operational system, and failures detected in the running system could be avoided when operating the second unit.

The boiler in this system is a once-through (as opposed to a recirculating) boiler. On Earth, supercritical once-through boilers are controlled tightly in conjunction with the turbine, and a turbine bypass system is typically used to shunt excess vapor around the turbine to protect it from being overdriven. If only one of the two power conversion loops is operated at any time, a failure of the turbine or alternator or a disconnection from the grid would require an immediate and significant reduction in reactor power unless a bypass system were available to dissipate the energy stored in the system and prevent damage to the primary system. If two secondary systems were operational, one could handle additional load in the event of a failure in the other and essentially serve as a bypass system.

The decision to have a turbine bypass system is dependent upon the selection of the operating modes, and it is ultimately dependent upon whether the system can safely handle anticipated failures without a bypass system. The bypass system could be an actively controlled system, or it could be a passive pressure relief system. The need to have a bypass system can be sufficiently evaluated through the use of computer simulations, so experiments relating to it are not necessary at this time.

3.3 ACCUMULATOR

Rankine systems that utilize liquid metals for the working fluid can be designed to be launched with the reactor coolant and the working fluid in the liquid state and begin operation before the system has time to cool to the point where the fluids freeze. It is possible that after the reactor has operated for a sufficient duration, fission product decay heat will allow the fluids to remain liquid long enough after a shutdown to facilitate a restart. Otherwise, the system must be designed to handle the contraction and expansion of the metal as it freezes and then rethaws.

The need for an accumulator is driven by (1) the need to accommodate thermal expansion of the working fluid during temperature changes and (2) the need to empty individual system components prior to the working fluid freezing if the eventual thawing of the fluid could potentially damage the component. Terrestrial experience is generally limited to (1) never allowing the metal to freeze while in the system and (2) draining a system completely if it is to be shut down. The ability to allow the metals to freeze and thaw in the system as opposed to being completely drained to an accumulator must be investigated experimentally at the component level. A strategy that uses an accumulator to store a portion of the working fluid while the remainder is held in critical locations within the system during a shutdown may work as well.

The expansion of the working fluid can either be accommodated within components already in the system, such as the condenser, or the expansion can be handled within a supplemental accumulator. An accumulator operating in microgravity cannot operate by having a fixed volume and simply allowing fluid to be inserted and removed from the volume as needed. Unless the fluid is held in position (utilizing surface tension effects or centrifugal forces for example), it would tend to float within the volume unpredictably. Alternatively, accumulators can have a variable volume that can be mechanically increased and decreased to pull fluid into it or expel fluid from it. A variable-volume accumulator can be a passive spring-loaded, pressure-driven device, or it can be actively driven by an actuator.

The accumulator has conflicting requirements during a shutdown sequence. The PCS coupled to the radiator system is the primary means of heat loss from the reactor coolant loop, and it must remain operational (have adequate working fluid inventory) until the decay heat from the reactor has reduced to the point that conduction through the system is sufficient to maintain safe temperatures. During the cooldown, the secondary system must accommodate working fluid contraction to keep key components filled while ensuring that components that must be drained are drained prior to freezing.

3.4 VALVES

All actuated components represent a concern for reliable operation, and any penetrations through the pressure boundary are locations where the potential for a loss of inventory is increased. The number of active components and pressure boundary penetrations should be minimized, but having some valves in the system appears unavoidable.

It was concluded in the MPRE program that inventory distribution could be made inherently stable by design at full-power operation without the use of throttling valves at the turbine inlet or the boiler inlet.[2] It is not clear if inventory control was thoroughly considered during the start-up sequence of the MPRE system. It may be possible to design a system that does not require control valve actuation during normal operation using the scheme proposed for the MPRE systems. However, it is unlikely that control valves will not be required during start-up where inventory management is likely to be the key control issue.

In the design proposed here, the secondary-side TEM pump begins pushing potassium through the power conversion loop as temperatures increase, and initially this flow may need to be prevented. Unless the system is designed to allow liquid to pass out of the top of the boiler, the secondary system could enter a configuration from which recovery may not be possible. Liquid flow out of the boiler should not be allowed to enter the main turbine, and it should only be allowed to enter the vapor inlet line running from the boiler to the boiler feed turbopump if the system is specifically designed to accommodate it.

It may be possible to switch the TEM pump on and off as required during start-up. However, this would not necessarily alleviate the need for a boiler inlet control valve. Toward the end of the initial phase of the start-up process, the boiler feed pump turbine would begin to rotate. When this happens, a temporary flow imbalance would occur, and liquid would be forced into the boiler at a rate higher than it is being boiled away. The flow out of the pump will require throttling unless the system is either designed to accommodate boiler overflow or an active accumulator is used to temporarily divert flow. The use of an accumulator is inherently transient however, because of the limited volume available within the accumulator.

The two methods of controlling the liquid flow rate into the boiler during normal operation are (1) controlling the vapor flow rate into the main pump (which controls the rate at which the pump spins and forces liquid into the boiler) and (2) regulating the flow rate of liquid into the boiler independent of pressure behind it using a valve. If the flow rate is not controlled mechanically, it must be matched thermally by matching the rate of energy flowing into the boiler to the desired working fluid evaporation rate. This may be possible during normal, steady state operation. During start-up and transients however, it may be more difficult to balance flow and power in the boiler because of the relatively small volume (<2 L), high-flow rates (>10 g/s), and the relatively long response time associated with increasing system temperatures.

3.5 COMPONENTS NOT CONSIDERED

In case of an electrical load reduction, excess electrical energy will be dumped to the parasitic load radiator (PLR) incorporated into the PCS design and radiated to space. It is assumed that the PLR will not feed back into operation of the system and impact operation. The PLR should be sized to handle full load at least temporarily in case the power supply is suddenly disconnected from the grid.

A rotary fluid management device (RFMD) may be required to properly handle cycle transients that occur at higher power operation that may allow vapor to be pulled from the condenser. If an RFMD is used, its accumulator could potentially be used for inventory management during start-up; however, it is not considered in the analysis of the system start-up because any liquid leaving the condenser during the start-up sequence is likely to be subcooled, and phase separation would not be required. The RFMD would be located between the condenser and the inlet to the boiler feed pump. If a boiler inlet flow control valve were included in the system, then the control valve would be located between the boiler feed pump outlet and the boiler inlet. The use of the RFMD accumulator would not necessarily alleviate the requirement for an additional accumulator connected directly to the boiler.

4. SYSTEM OPERATION

4.1 FOUR-VALVE CONTROL STRATEGY

As more valves are added to the control strategy, it becomes easier to control inventory during the start-up sequence. The cost however is additional mass and an increase in the number of possible failure modes. The most probable valve locations are

1. boiler inlet,
2. turbine inlet,
3. boiler feed pump turbine vapor inlet, and
4. turbine bypass inlet.

A schematic illustrating the major system components and the measurement points of a possible four-valve control scheme is shown in Fig. 2. An accumulator is shown although it may not be required. Lithium lines are shown in blue, and potassium lines are shown in green. Red lines represent electrical connections. Each of the proposed valves would be repeated for the two power conversion loops. For simplicity, the operation of only one loop is discussed. A control strategy with the following features could potentially be utilized if four control valves are available:

1. Operate the reactor at a level to match demand.
2. Use heat from the reactor to warm the PCS using a shroud enclosure, heat pipes, and/or internal capillary structure.
3. Isolate the boiler to allow pressure and temperature to increase.
4. Open the valves, allowing vapor flow to the boiler feed pump turbine and liquid return to the boiler.
5. Direct excess vapor flow to the bypass system to accommodate variable power loads and transients.
6. Open the main turbine inlet valve, allowing a portion of the vapor flow to spin the turbine.
7. Direct initial electrical power output to the primary-side ALIP to increase primary coolant flow, allowing increases in reactor power and, ultimately, vapor production rates.

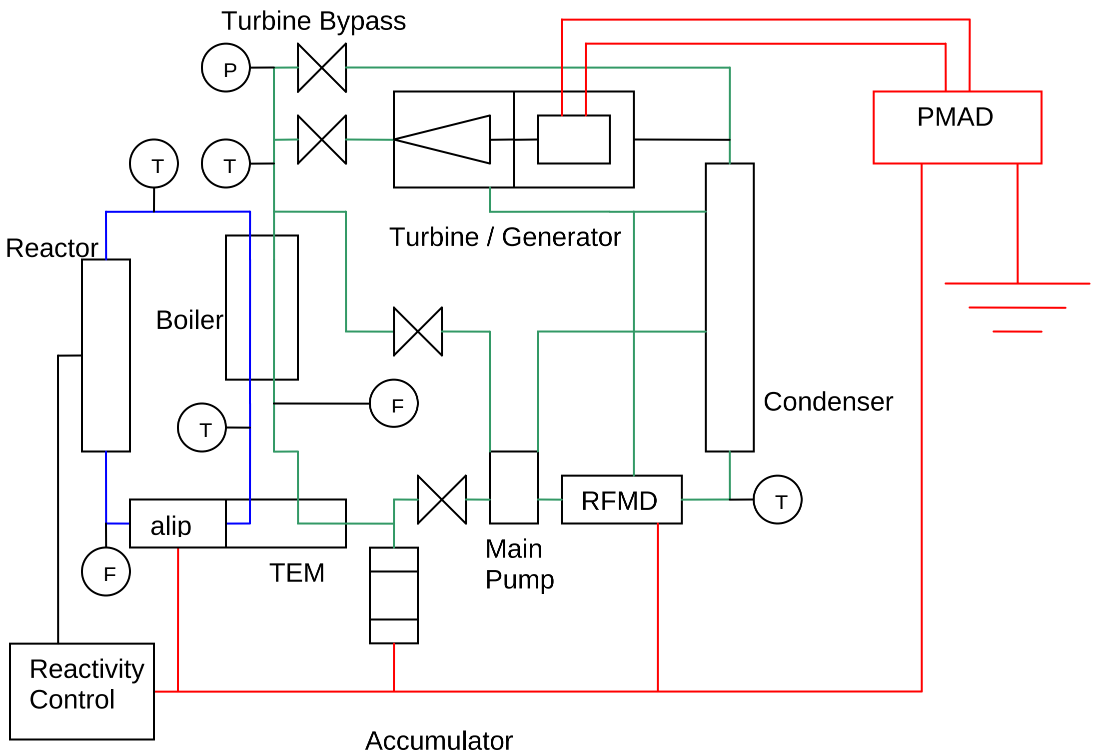

Fig. 2. Schematic of a possible secondary-system control system showing major components and required measurement points using a four-valve control strategy.

Control of the system is greatly simplified if a direct measure of the liquid level in the boiler is available. However, in microgravity a direct level measurement is difficult, and it may not be possible especially under low-flow conditions. During normal steady state operation, the required flow rate into the boiler can possibly be matched to the reactor power. However, transient events and measurement error (especially during the start-up sequence) drive the need for an inventory control scheme.

In the absence of a direct measurement of boiler inventory, it may be possible to infer the liquid level position within the boiler tubes from available direct measurements such as reactor power, boiler inlet flow rates, and inlet and outlet temperatures. This approach, however, serves only as a guide to determining the required potassium flow rate, and it does not prevent underfilling or overfilling of the boiler tubes. Electromagnetic flow meters are assumed to measure the flow rate of liquid lithium and liquid potassium in the system. Although it is presumed that these measurements will be augmented by other methods, such as cross-correlation analysis of directly read measurements, none of the measurement techniques will be extremely accurate during the low-flow conditions of start-up.

A direct method of inferring the liquid level in the secondary tubes (or whether the level is within an acceptable range) is highly desirable. The boiler tubes are curved in the present design. The curvature prevents a direct line of sight measurement down the tube; however, it may be possible to straighten the outlet section of the tubes to accommodate a direct line of sight measurement, such as interferometry. In the absence of a direct line of sight measurement, it is possible that acoustic measurements may be able to provide an indication of the liquid level in the tubes.

4.2 TWO-VALVE CONTROL STRATEGY (CONTINUOUSLY OPEN START LOOP)

Some isolation valves in the system could potentially be eliminated in conjunction with appropriate start-up and operation strategies. The MPRE program proposed an operational scheme that eliminated the use of a main turbine inlet valve.[2] The boiler feed turbopump vapor inlet isolation valve could potentially be eliminated by allowing a continuously open start loop, defined as a contiguous path from the boiler outlet through the boiler feed pump turbine to the condenser and returning to the boiler through the liquid side of the boiler feed pump. In this configuration, flow gradually increases through the loop as system temperatures and pressures increase.

The start loop includes the line from the boiler to the condenser that passes through the turbine of the boiler feed pump. The main feed pump turbine would be sized (in conjunction with the line feeding it) to drive the boiler feed pump so that it provides the potassium flow at or above the maximum required flow rate at normal full-power operating temperatures and pressures. The boiler inlet flow would require regulation at the boiler inlet unless the dynamically stable flow regime reported in the MPRE program can be achieved.

Vapor flow in excess of that required to drive the boiler feed pump (~10 g/s) must be routed to the condenser in some path other than through the boiler feed pump turbine. If a bypass system is not utilized in the design, then the excess flow must pass through the turbine, which means that it must be at adequate temperature to prevent potassium condensation in the turbine. A schematic illustrating the major system components and the measurement points of a possible two-valve control scheme is shown in Fig. 3. Lithium lines are shown in blue, and potassium lines are shown in green. Red lines represent electrical connections.

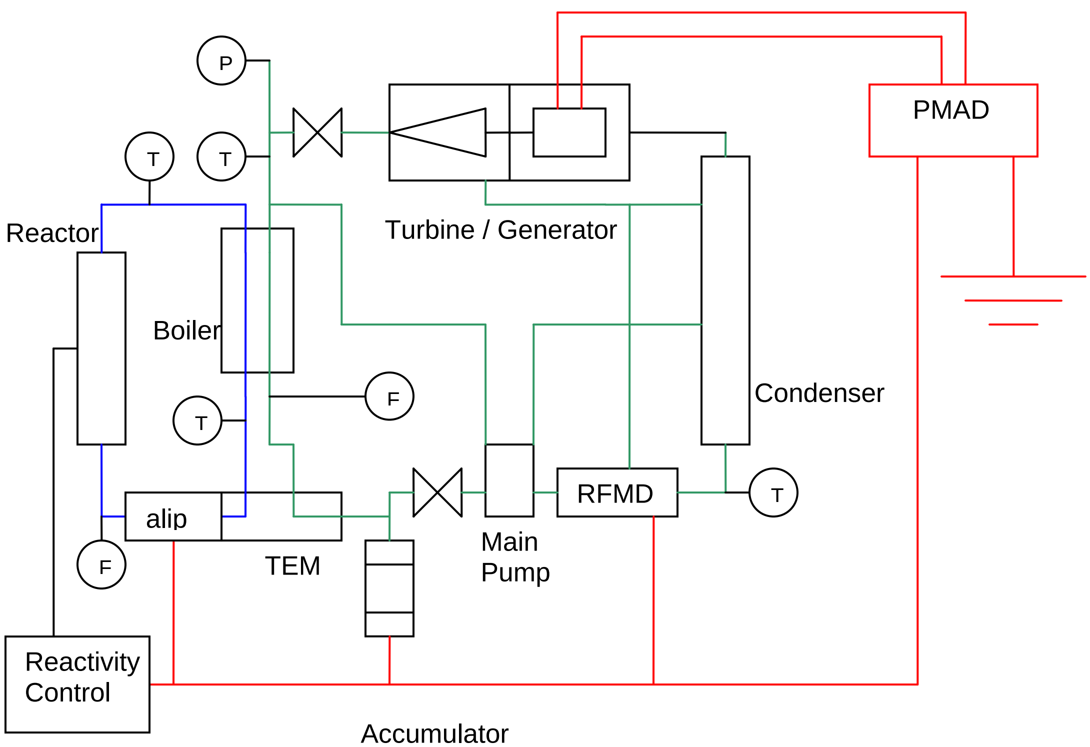

Fig. 3. Schematic of a possible secondary-system control system showing major components and required measurement points using a two-valve control strategy.

5. EXPERIMENTS

Four issues stand out as requiring experimental verification to validate the possible control strategies discussed previously. The experiments required to simulate the start-up conditions for the Rankine system do not require a precise match of thermal-hydraulic conditions as do the microgravity scaling experiments.[3] The purpose of the experiments is to determine how the system would behave during various phases of the start-up sequence.

The behaviors of the loop that are of interest include the determination of whether individual components can withstand freeze/thaw cycles, the ability to control inventory under low-flow and low-pressure conditions, and the ability to start the system with a continuously open start loop. Of these, the most difficult requirement to test is the ability to control inventory in the absence of a gravitational field under low-flow conditions.

5.1 THE ABILITY TO FREEZE AND THAW WORKING FLUIDS WITHIN THE SYSTEM COMPONENTS WITHOUT DAMAGE

The ability to freeze and thaw the working fluid within components can best be demonstrated with the actual fluid proposed for operation. Ultimately, potassium would be inserted and frozen and thawed through several cycles within prototypic components. In situ strain gauge readings would be taken during the expansion and contraction process. The components would be drained, cleaned, and inspected for damage. The experiments would determine the stress imposed on thin-walled components and on internal structures due to expansion and contraction of the working fluid in the thawing and freezing process and compare them to coupled thermal and structural models of the components. The intent would be to quantify the mass penalty or thermal transport penalty associated with designing the component to preclude damage under those conditions. If the mass penalty is too great, the component may have to be drained during the shutdown process. The components whose configuration should be tested include (1) simple pipe structures, (2) the boiler tube arrangement, and (3) the condenser arrangement.

These tests would ultimately be performed with potassium. Paraffin wax is proposed as an initial surrogate fluid to test the ability to freeze and thaw in the system without having to cool the system below room temperature. Paraffin tests would be performed to learn how liquids would flow and how and where solids would form in systems as their temperatures are varied. These experiments would be followed by more definitive experiments with potassium.

5.2 THE ABILITY TO BOOTSTRAP A CONTINUOUSLY OPEN START LOOP TO MINIMIZE THE NUMBER OF CONTROL COMPONENTS REQUIRED WITHIN THE SYSTEM

If a successful continuously open start loop arrangement can be configured, it may allow the elimination of all but two PCS control valves (per loop). This represents a significant improvement in overall system complexity. The features that are required to implement a continuously open start loop include the following:

1. a TEM pump that preferably has control capabilities,
2. a condenser that manages inventory at low flow and pressure and works in conjunction with the primary vapor loop when the turbine inlet valve is open,
3. a main potassium pump that allows liquid inventory to pass through the drive side, and
4. a means of accommodating the thermal expansion of potassium during the start-up process either in the condenser or in a separate accumulator.

To experimentally verify a continuously open start loop, the following components would be required:

1. boiler system,
2. an electrically driven pump programmed to operate as the TEM pump,
3. a condenser replicating the geometry of the proposed system condenser,
4. a prototype of the main potassium pump,
5. valve to represent the turbine inlet valve, and
6. turbine simulator (orifice for pressure drop and active cooling).

These experiments would be performed initially with fluids that are liquid at room temperature such as FC-72 or cyclohexane. FC-72 is a liquid at room temperature and boils at 56°C. The material is essentially inert and has low toxicity. Scaled experiments to replicate the thermodynamic conditions in the boiler and the condenser are being planned for low-gravity experimentation using FC-72 (Ref. 3). Therefore, experiments used to test the start-up of the system can be easily coordinated to the planned flight experiments if FC-72 is used. FC-72 has too low a freezing temperature to allow for solid testing.

Cyclohexane is solid at 6°C and can be frozen by a chilled water system. Cyclohexane boils at 82°C and can therefore be boiled with water at atmospheric pressure. Cyclohexane therefore is an excellent candidate to perform start-up experiments that begin with the system below the freezing point of the working fluid and extend in temperature to the boiling point of the working fluid. It will allow the start loop to be tested from shutdown through a restart and back to the shutdown condition. These experiments would be performed by using separate water systems to control the heat input into the boiler and heat removal from the condenser. It is probable that the system could be fabricated on a small enough scale to allow it to be rotated against gravity during operation.

5.3 THE ABILITY TO CONTROL LIQUID INVENTORY LEVELS WITHIN THE BOILER IN THE ABSENCE OF A DIRECT LEVEL MEASUREMENT

The system described in Sect. 5.2 would be used to demonstrate how a system start-up could occur. Additional work is required to determine if start-up can occur given the measurement values likely to be available in microgravity. Specifically, techniques that allow the liquid level in the boiler to be controlled in the absence of a direct reading would be investigated. Testing would evaluate the ability to control liquid level in the boiler through the use of measurements expected to be available on the potassium Rankine PCS. Transient events would be initiated and the system response recorded and compared to simulation models. The tests would be performed with FC-72. Operation specifically relevant to start-up in microgravity conditions is difficult to perform at bench top scales, or within the time frames allowed by drop tower or aircraft testing. Ultimately, these experiments would be best suited for orbiting platforms like the shuttle and the space station after initial laboratory experiments are successfully completed.

5.4 THE ABILITY TO OPERATE A CONDENSER AT LOW-POWER AND LOW-FLOW RATES IN THE ABSENCE OF A GRAVITATIONAL FIELD

The most difficult issues to resolve are those related to operation of a two-phase system in microgravity. Two-phase operation is likely to be manageable at full power where flow rates can be high enough to use viscous and centrifugal forces to control liquid and vapor interfaces. At lower powers and lower flows, these forces may not be dominant enough to force the inventory where it is needed.

Capillary forces would be investigated to determine how they can be used in the condenser and the piping of the start loop to ensure proper inventory location during shutdown and restart sequences. A condenser design that permits operation of the start loop and allows seamless operation with the main condenser over all operating conditions would also be developed and tested. FC-72 and cyclohexane are proposed as the simulant fluids for these tests.

6. CONCLUSIONS

The start-up experiments that will be most beneficial to the development of a Rankine system for operation in microgravity are related to the following:

1. demonstration of component configurations not susceptible to damage during the freezing and thawing of potassium and assessment of their required mass,
2. demonstration of the ability to minimize the active components in the system by starting the system with a continuously open start loop, and
3. demonstration of the ability to control working fluid inventory during low-power and low-flow conditions.

Structures that could possibly use capillary action to maintain liquid inventory in the boiler feed pump suction line and other desired locations would be investigated. FC-72 and cyclohexane are proposed for these experiments. Cyclohexane is proposed for more elaborate experiments that would involve actively cooling the experiment to below $6^{o}C$ where the cyclohexane would be solid and heating the experiment to the boiling temperature ($82^{o}C$ at atmospheric pressure). These experiments would simulate the entire start-up sequence up to rotation of the boiler feed pump and return to the shutdown condition. A prototype boiler feed pump would ideally be developed and tested in conjunction with the experiments. The TEM pump would be simulated by an electrically driven variable-speed pump. Heat input into the boiler and the condenser would be controlled to simulate operation in a space environment from cold (solid) conditions to initial rotation of the main pump. It is probable that the system could be fabricated on a small enough scale to allow it to be rotated against gravity during operation for bench top testing.

Transient flow experiments would be conducted on a similar test loop to investigate the ability to control the liquid level in the boiler without a direct liquid level measurement. Operation specifically relevant to start-up in microgravity conditions is difficult on a bench top experiment, and within the time frames allowed by drop testing or aircraft testing. Ultimately, the transient experiments would be best suited for orbiting platforms like the shuttle and the space station after initial laboratory experiments are successfully completed.

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