AN ORGANIC RANKINE RECEIVER FOR THE SCSTPE PROGRAM

by

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ABSTRACT

This paper presents a brief description of an Organic Rankine Cycle (ORC) Receiver which is presently being developed for the SCSTPE Phase II program. The receiver employs an integrated cavity/pool boiler* which permits the design of a small, lightweight, low cost and efficient moderate temperature receiver for use in a dish-Rankine PFDR system.

INTRODUCTION

Under the SCSTPE (EE#1) Phase II Program, FACC will develop a PFDR solar thermal electric system employing Rankine-cycle Power Conversion Assemblies (PCAs) mounted at the focus of Parabolic dish concentrators. The PCA consists of a receiver, organic Rankine cycle (ORC) engine and high-speed AC generator (Figure 1). The design of the receiver is a major technical challenge in the development of this PFDR system. Cavity-type receivers are generally most efficient for moderate and high-temperature systems. There are, in general, two types of cavity receivers:

- Direct heated, where the engine working fluid is heated within the receiver.
- Indirect heated, where a secondary fluid is heated in the receiver and the primary (engine working) fluid is heated in a separate heat exchanger.

Each approach has advantages and disadvantages, strongly influenced by system considerations. For the SCSTPE Phase II Program, FACC has chosen to try an indirect heated design, based on a concept studied in depth during the Phase I part of the program. The most important difference between the Phase I and Phase II efforts, however, is the operating temperature range. The high temperature (800°C) Stirling engine studied during Phase I resulted in the selection of sodium for the receiver fluid. The moderate operating temperature (427°C) of the Phase II ORC requires the search for a more applicable fluid.

SUBSYSTEM DESCRIPTION

A sketch of the baseline receiver configuration is presented in Figure 2. The cavity receiver is a simple structure consisting of two cylindrical shells, one cantilevered inside the other from a connecting toroidal shell. The two ends are capped with spherical heads forming a

*Patent applied for

design with minimal modifications. For example, canisters of high thermal capacity materials (i.e., eutectic salts) can be inserted within the receiver annulus, with energy transfer facilitated by the high boiling heat transfer coefficients of the secondary fluid. The fully insulated receiver (12.7 cm of insulation) can accommodate a maximum 100 kW_t energy within a 1 x 1 x 1.2 m envelope at a gross weight of 180 kg including 20 kg of a typical fluid. Based on Phase I vendor quotations, the complete receiver/thermal transport package can be manufactured for under $2500 when built in production quantities. The operational life of the optimized, lowest life cycle cost receiver is selected at 15 years, based on design tradeoffs between material corrosion rate and material creep-rupture limitations.

BENEFITS OF POOL BOILING RECEIVER

The heat transfer coefficients associated with pool boiling are very high and generally result in:

- Reduced cavity area (thus, a lighter and lower cost receiver)
- Reduced receiver-to-engine temperature differential (reduces thermal losses and thus increases system efficiency)
- Reduced sensitivity to the incident flux levels (thus a large safety factor against temperature overshoot or burnthrough).

Other benefits include a simplified design that does <u>not</u> require tubes, fins, flux adjusters, pumps or special controls. By selecting the right fluid, the vapor pressure at the steady-state operating temperature can be about 1 atmosphere. This virtually eliminates any pressure differential, hence reduces the cavity wall thickness which in turn reduces the temperature gradients, weight and cost of the receiver. The thermal inertial of the receiver cavity walls and boiling pool provide an inherent buffer storage capability during short inclement operating conditions such as those associated with a cloud passage. The thermosyphon also operates at a nearly constant temperature.

The condenser/heat exchanger also has very high film coefficients. This permits a heat exchanger configuration and surface geometry to yield a small compact unit without concern about the solar flux distribution and levels.

PRELIMINARY FLUID SELECTION

Some of the more important characteristics of the receiver fluid are listed below.

- Critical point above the maximum operating conditions of the engine working fluid.
- High boiling heat transfer coefficients.
- High burnout heat flux.

- Stable pool boiling for a range of operating conditions.
- Low vapor pressure at operating temperature.
- Non-corrosive, non-toxic, non-flammable and chemically stable.
- Easy to handle and fill/drain receiver.
- Freeze point below ambient conditions.
- High heat capacity.
- Low cost.

As previously mentioned, sodium was selected for use in the high temperature (~800°C) receiver. At the lower operating temperatures of ORC engines (~350-425°C), several candidate fluids exist subject to further investigation. These fluids include the various terphenyls, sulfur, aluminum bromide, etc.

PERFORMANCE

Figure 3 presents a comparison of typical boiling and gas-in-tube heat transfer rates. As shown, the boiling systems have much higher heat transfer rates than those for forced gas convection; also less heat transfer surface area is required and lower temperature differentials between the surface and the working fluid are experienced. Reference 1 indicates that sulfur (with a small amount of iodine to reduce the high viscosity at lower temperatures) has comparable performance to water in a heat pipe application. In addition, the burnout heat flux for sulfur is approximately 1000 kW/m^2 at a pressure of 1 atm (Reference 2). This gives a safety factor of approximately 3 over the predicted worst case flux deposition for a typical cavity receiver configuration.

Figure 4 shows the vapor pressures of various heat transfer fluids as a function of temperature. The vapor pressures of the terphenyls and sulfur are approximately 1 atm at the upper operating temperature (~427°C) of ORC engines. The vapor pressure of aluminum bromide is slightly higher. In the case of the terphenyls and sulfur, the net pressure loading on the receiver is very low, with obvious structural and safety advantages.

The temperature gradients throughout the receiver subsystem are presented in Figure 5. The largest temperature drop occurs through the receiver wall. The backface wall-to-pool temperature differential is typically quite small due to the high heat transfer coefficients characteristic of the pool boiling phenomena. The temperature drop through the vapor pipe is predicted to be on the order of a few degrees centigrade, due to the pressure difference between the pool and heat exchanger. A very small temperature drop is also predicted for the condensation heat transfer to the secondary heat exchanger. The temperature drops through the secondary heat exchanger will be minimized by utilizing a high performance plate-fin configuration.

Transient Operating Characteristics

An in-depth transient analysis of the receiver/thermal transport subsystem is necessary in view of the inherent non-steady nature of the

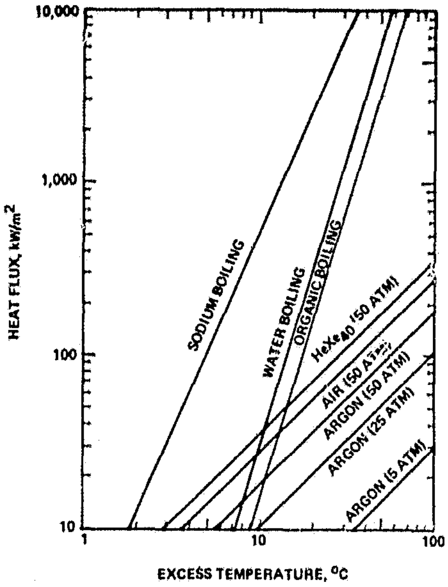

FIG. 3. BOILING AND GAS-IN-TUBE HEAT TRANSFER

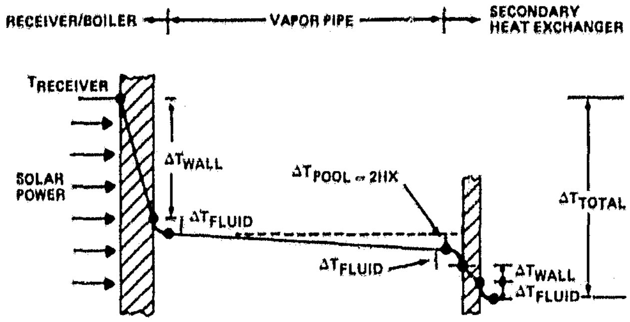

FIG. 5. SUBSYSTEM TEMPERATURE GRADIENTS

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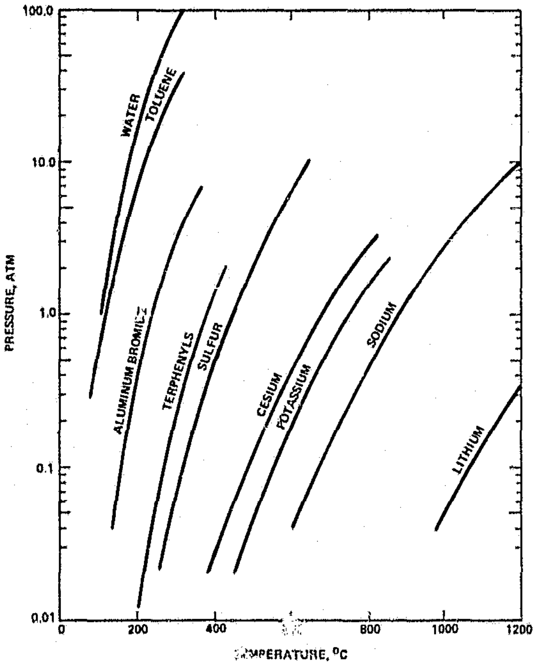

FIG. 4. VAPOR PRESSURES FOR SEVERAL HEAT TRANSFER FLUIDS

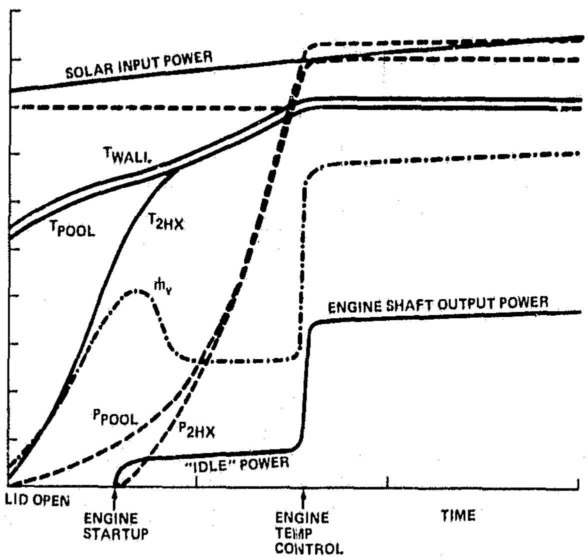

FIG. 6. SUBSYSTEM RESPONSE DURING NORMAL STARTUP

solar flux. The objective is to characterize the behavior of the subsystem for all operational modes encountered in a solar application. During Phase I, a transient thermal model was developed from the basic equations for conservation of mass, conservation of energy, the equation of state for vapor, and the vapor pressure equation. It is assumed that the vapor is saturated (vapor and liquid in quasiequilibrium), the vapor volume is approximately constant and that the receiver orientation effects are negligible. The energy balance considered the incoming solar power, the thermal power to the engine, and the thermal losses from the subsystem. Pressure drops throughout the entire transport subsystem were also included. Typical results of the transient analysis are discussed below.

NORMAL START-UP. Figure 6 presents the subsystem temperature response and engine output power during a normal start-up condition. The solar input power profile is based on the 15 minute Barstow, California solar insolation data for a typical uncloudy day and includes the effects of both concentrator size and efficiency, thus representing the total power entering the receiver. In the morning, after normal operation from the previous day and nighttime cool down, the receiver pool is still warm. The receiver lid is opened prior to focusing on the sun. Once the sun is "on", the pool and heat exchanger temperatures rapidly increase towards the steady-state operating level. The pool and heat exchanger temperatures correspond to the saturated vapor pressure at the respective temperatures. The temperatures, pressures, and vapor mass flow rate increase as the solar energy continues to enter the system. After several minutes the engine head temperature has reached the predetermined start temperature. The engine is then started and operated at a low or "idle" power level consistent with a previously selected condition. After several more minutes, the engine working fluid reaches the steady-state operating temperature (427°C) and the engine temperature control mode is activated. At this point the temperature controller is modulated to maintain the engine temperature within the control band as the solar flux varies during the day.

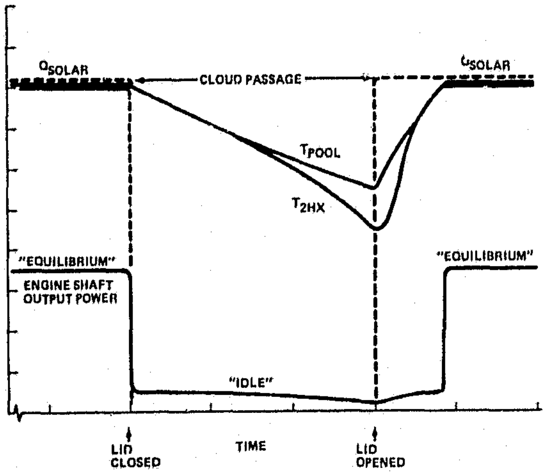

FIG. 7. SUBSYSTEM TEMPERATURE RESPONSE DURING CLOUD PASSAGE

CLOUD PASSAGE. Figure 7 presents the subsystem temperature response during a typical cloud passage. As the cloud passage starts its passage, the solar input power goes to zero, the receiver lid closes and the subsystem temperatures start to decrease. The engine output power will decrease until operation is at a low or "idle" power level. During cloud passage the receiver pool and engine fluid temperature decrease while the engine "idle" power remains relatively constant. When the cloud has passed, the solar power returns and the receiver lid is opened allowing the subsystem temperatures to increase. Several minutes are required to heat the subsystem back up to the steady-state operating temperature.

The results of all of the cases investigated during Phase I of the program demonstrate that the performance of the subsystem is stable, well-behaved, and has long thermal time constants which facilitate engine control.

CONCLUSIONS

An ORC receiver utilizing an integrated cavity/pool boiler is technically feasible at the present time and uses state-of-the-art materials. The use of a pool boiler permits the design of a small, lightweight, low cost and efficient, moderate temperature receiver for use in a dish-Rankine PFDR system.

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