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THE BUBBLE MEMBRANE RADIATOR

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MODELING THE FILM CONDENSATE FLUID DYNAMICS AND HEAT TRANSFER
WITHIN THE BUBBLE MEMBRANE RADIATOR

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Abstract

An analytical model of the fluid dynamics and heat transfer characteristics of the condensate within the rotating Bubble Membrane Radiator is developed. The steady-state, three-dimensional heat transfer and flow equations were reduced to a set of third-order ordinary differential equations by employing similarity transformation techniques. These equations are then solved for the radial, axial, and angular flow distributions in the film condensate. Pressure, temperature, heat transfer, film thickness and mass flow rate distributions are also calculated. The analytical model is the basis of the SCRABLE code which is used both as a zero-g design tool and a ground-test bed analyzer.

INTRODUCTION

The Bubble Membrane Radiator (BMR) is a member of a unique class of spacecraft thermal management devices which combine low-mass and low-launch volume with superior thermal performance and survivability. The BMR is an enclosed two-phase radiator which rotates about a central axis and consists of nine major components (See Figure 1): the attachment boom, rotation platform, central rotating shaft, central spray nozzle, thin film radiating surface, fluid collection troughs, pitot pumps, return piping and structure, and main feed/return lines. The common characteristic of this class of radiators, referred to as 'fabric radiators,' is the utilization of ultralite fabric (UF) composite materials.

The goals in the development of the BMR have been the reduction of cost-to-orbit, as well as increased systems efficiency and thermodynamic performance for space-based thermal management systems. To accomplish these criteria, a heat rejection system must transport significant quantities of thermal energy from the cycle working fluid and reject this energy directly to space. The BMR is a hybrid radiator design which incorporates the high surface heat fluxes of conventional heat pipes and the low system masses associated with liquid droplet radiators.

This paper documents work performed during the second phase of development of the BMR to predict the thermal hydraulic behavior of the condensate within the BMR under microgravity and 1 G conditions, for a variety of configurations. The specific phenomena of interest were condensate flow velocity, pressure gradients, temperature profiles, mass flow rates, condensation flow rates, condensate film thickness, heat transfer coefficients, and laminar-to-turbulent transition.

The Steady State Condensation with Rotational Acceleration Boundary Layer Examiner (SCRABLE) was written to determine the thermal hydraulic behavior of the BMR. The SCRABLE code analyzes both spherical and plate geometries with and without rotation.

The theory used in the SCRABLE code draws upon work in describing film condensation on spherical and rotating surfaces.

FIGURE 1. Spherical Bubble Membrane Radiator Design.

Film Condensation on a Non-Rotating Sphere

The heat and mass transfer phenomena associated with laminar film condensation on a spherical surface have been studied previously by Yang (1973). Yang developed a similarity transformation for the mass, momentum, and energy conservation equations as outlined below.

The coordinate system, shown in Figure 2, was selected to simplify the derivation of the conservation equations. The x -direction is arc length and the y -direction is the nominal radial distance from the surface. The origin is set at the upper flow stagnation point.

FIGURE 2. Spherical Coordination System for Modeling of the Bubble Membrane Radiator.

The sphere is assumed to be immersed in an infinite body of pure vapor at its saturation temperature, called T_{sat} . The surface of the sphere is maintained at a uniform temperature, T_w . For laminar film condensation, a stream function representation using the Sparrow and Gregg (1959) similarity transformation of the steady, nondissipative, axisymmetric, constant-property flow is as follows:

$$f''' + 2ff'' - f'^2 + 1 = 0 \quad \text{and} \quad (1)$$

$$\Theta'' + 2Prf\Theta' = 0 \quad (2)$$

The boundary conditions for these equations are:

$$\begin{array}{ll} \text{at } \eta = 0 & \text{at } \eta = 1 \\ f = 0 & f' = 0 \\ f' = 0 & \Theta = 0 \\ \Theta = 1 & \end{array} \quad (3)$$

The similarity transformation uses the dimensionless variable η , defined as

$$\eta = y C^{1/4} G/R, \quad (4)$$

to derive the velocity function f and the dimensionless temperature Θ . The transformation equations for f and Θ are

$$\psi = \nu C^{1/4} Hf(\eta) \quad \text{and} \quad (5)$$

$$\Theta = (t - T_{sat}) / (T_w - T_{sat}) \quad (6)$$

Film Condensation on a Rotating Disk

By creating an artificial body-force in the presence of film condensation, the heat transfer rate from the vapor to the condensing surface may be increased. Sparrow and Gregg (1959) explored the analysis of the flow and thermal behavior of laminar-film condensation on a horizontal plate. The system under consideration, shown in Figure 3, is a cooled rotating disk at a uniform temperature, T_w , located in an infinite body of pure saturated vapor. A film is assumed to form on the disk surface and will migrate radially outward under the influence of the centrifugal force field.

FIGURE 3. Rotational Coordinate System for a Flat Plate Geometry.

With some insight from Von Karman (Schlichting 1955), a similarity transformation may be made using the following new variables:

$$\eta_1 = \left(\frac{\omega}{\nu} \right)^{1/2} z \quad (7)$$

$$F(\eta) = \frac{V_r}{r\omega} \quad (8)$$

$$H(\eta) = \frac{V_z}{(\omega r)^{1/2}} \quad (9)$$

$$P(\eta) = \frac{p}{\mu\omega} \quad (10)$$

and

$$\Theta(\eta) = \frac{T_{sat} - T}{T_{sat} - T_w} \quad (11)$$

Two assumptions are made concerning directional dependence. First, there is angular symmetry such that $\partial/\partial\phi = 0$. Second, the shape of the velocity profiles in the r and f directions is constant in the radial direction. This implies simple stretching of a fundamental shaping function at various values of r . This yields:

$$H''' = HH'' - (H')^2/2 + 2G^2 \quad \text{and} \quad (12)$$

$$G'' = HG' - H'G \quad (13)$$

The transformed boundary conditions are

at $h = 0$ $H = 0$ $H' = 0$ $G = 1$ $\Theta = 1$	at $h = h_0$ $H'' = 0$ $G' = 0$ $\Theta = 0$	(14)

Rotational Superposition

To model condensation of the rotating sphere, the profiles of the spherical non-rotating and rotating flat plate boundary layer velocities were superpositioned (see Figure 4). The relationship between the x and r coordinates in Figure 4 is found to be

$$r = R \sin(x/R) \quad (15)$$

This yields an effective radius for use in the boundary conditions for the rotational flat plate solution. Both the flat plate and non-rotating spherical models are solved and the velocity and temperature profiles are combined by superposition at each value of x .

FIGURE 4. Superposition coordinate system.

OPERATION OF THE SCRABLE CODE

A typical set of results from the SCRABLE code are presented for the conditions found in Table 1.

TABLE 1. Sample Conditions input to SCRABLE Code

Input Parameter	Parametric Values
Working Fluid	Water
Inlet Vapor Temperature	600.0 K
Heat Rejection Capability	10.0 kW
Surface Emissivity	0.90
View Factor	1.00
Space Environment Temperature	2.00 K
Radiator Radius	1.91 m
Rotational Speed	10.00 rpm

Figures 5 and 6 illustrate the predicted flow distributions over the condensate film thickness at two points on the radius. The dimensionless pressure and temperature profiles over the film thickness are shown in Figure 7.

FIGURE 5. R-directional Velocity Component over the Film Thickness at Two Radial Locations.

FIGURE 6. Theta-direction Velocity Component over the Film Thickness at Two Radial Locations.

FIGURE 7. Dimensionless Temperature and Pressure over the Film Thickness.

The mean heat transfer characteristics of the film condensate are explained in Table 2. These values represent the average properties over the effective arc length from the stagnation point at the apex to the equator of rotation.

TABLE 2. Heat Transfer Characteristics of Film Condensate from the Sample Model

Output Parameter	Parametric Values
Film Thickness	0.000969 m
Nusselt Number	0.0014
Heat Transfer Coefficient	7140.238 W/m ² -K
Required Mass Flow Rate	0.007814 kg/s
Limiting Mass Flow Rate	0.716204 kg/s
Limiting Rejection Power	916.5808 kW

Due to the assumption made in the derivation of the governing equations, results from the SCRABLE code are valid only for steady, nondissipative laminar flow. Transition to turbulence will increase the heat transfer characteristics of the flow and further improve the capabilities of the BMR design. However, further modelling will be necessary for this condition.

The Pacific Northwest Laboratory is working with Oregon State University in analyzing the BMR Ground Test Bed and validating the performance of the SCRABLE code.

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Nomenclature

English

- x: arc length in Fig. 2
- y: outward normal direction in Fig. 2
- r: distance from axis of rotation in Fig. 2.
- R: distance from center of sphere in Fig. 2
- g: gravitational acceleration
- C: flow variable = $g(\rho - \rho_v) R^3 / \rho v^2$
- f: dependent dimensionless flow variable in Eq. 1.
- T_w : wall temperature
- T_{sat} : saturation temperature
- G: r- direction flow variable for plate development
- H: ϕ - direction flow variable for plate development
- F: z- direction flow variable for plate development
- J: x- direction flow variable for spherical development
- I: y- direction flow variable for spherical development
- P: dimensionless pressure

Greek

- η : Dimensionless independent variable defined in Eq. 4 and 7.
- ψ : stream function defined in Eq. 5.
- θ : dimensionless temperature
- ρ : density of condensate
- ρ_v : density of vapor
- ϕ : angular coordinate
- ω : rotational velocity

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