Computerized Thermal Modeling of Spacecraft Environmental Control Systems

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Nomenclature

A = surface area of tube in section of fluid duct
c_p = specific heat
G_i = conductance from vehicle structure to the average fluid temperature in a fluid duct section
h = heat transfer coefficient for convection
$m,\dot{m}$ = mass, mass flow rate
P = tube perimeter
Q_c = gas-liquid heat exchanger liquid heat load
Q_d = direct fluid heat load
Q_f = fan heat load
Q_n = net heat removed from cabin gas
Q_s = heat absorbed by water sublimator
T = temperature
$\langle T \rangle$ = average temperature for fluid in a duct, $(T_I + T_O)/2$
T_f = temperature of gas at gas-liquid heat exchanger fan outlet
T_g = cabin gas average temperature
T_I,T_O = inlet, outlet temperature to a section of fluid duct or a fluid element
T_s = average temperature of structure coupled to fluid
t = time
x = tube length
ϵ = gas-liquid heat exchanger effectiveness
ϵ_s = water sublimator effectiveness

Subscripts

g = cabin gas
l = liquid coolant

Introduction

LARGE, complex spacecraft require an active environmental control system (ECS). Manned space stations, space shuttles, and planetary vehicles will have complex gas and fluid systems which will be analyzed using thermal analyzer programs. This Note, reporting work done for the NASA Marshall Space Flight Center, presents a computerized modeling technique for ECS performance simulation which is general and can be used with any thermal analyzer program which permits FORTRAN external subroutines. The complete ECS model is represented as a set of steady-state equations in a thermal analyzer subroutine. This method was used to support the thermal design of the Apollo Lunar Module (LM) and to predict ECS performance for test and flight.[1–3] Writing the ECS subroutine, however, was cumbersome. A similar technique has been used in an independent thermal analysis of the LM ECS.[4] This approach uses a specialized computer program to solve the thermal equations and control the thermal balance of the loop. Because of a lack of generality, it would be difficult to extend this technique.

The deficiencies encountered in applying these techniques to a general ECS system have been overcome by the development of a new computer program entitled the Fluid Network Generator (FNG). Simplified fluid loop terminology is used to describe input to the FNG which punches the cards that form the main portion of the thermal analyzer ECS subroutine. The program has been written to punch FORTRAN equations and network cards for the CINDA thermal analyzer program.[5] These cards form the complete fluid subroutine for simple flow loop analysis or provide the skeleton model for more complex systems. Steady-state equations for active thermal subsystem components such as heat exchangers and water sublimators are added by the analyst and, when combined with the basic flow equations punched by the FNG, form the ECS subroutine for a complex system. FNG program is being used to support thermal analysis for the Apollo Applications Program cluster vehicle.

ECS Computer Subroutine Equations

The ECS computer subroutine, when used in conjunction with a thermal analyzer program, provides integrated thermal performance simulation of the flow loop and the vehicle structure. The ECS thermal subsystem components may be classified as passive (vehicle structure, radiator tube walls, and electronic equipment) or active (water sublimators, and liquid-liquid and gas-liquid heat exchangers). In addition, fluid loops are subjected to direct heat loads which may result from fluid pumps and from metabolic, chemical, and electrical heat generation. A typical ECS subroutine is composed of equations for these components.

The basic fluid flow equations used by the ECS subroutine to couple the passive vehicle structure to the fluid were adapted from a method outlined by Grafton.[6] The approximate one-dimensional heat-transfer equation for incompressible fluid flow in a duct of length Δx, with the assumption that the fluid temperature varies linearly along the duct, is

$$mc_p dT/dt = \dot{m}c_p(T_I - T_O) + hP\Delta x(T_w - T) \tag{1}$$

By neglecting the thermal mass of fluid in a section of the tube and generalizing to k conductances, each with a coupling of G_i to the average fluid, Eq. (1) can be solved,

$$\langle T \rangle = \left[2\dot{m}c_p T_I + \sum_{i=1}^{k} G_i T_{si}\right] \Big/ \left[2\dot{m}c_p + \sum_{i=1}^{k} G_i\right] \tag{2}$$

$$T_O = 2\langle T \rangle - T_I$$

These steady-state equations are used in the ECS subroutine to couple cold-plated electronic equipment, fluid ducts, tube walls, and arbitrary vehicle structures to the fluid.

The steady-state equation that represents the fluid's increase in temperature for a section of fluid duct as a result of a direct heat load is,

$$T_O = T_I + Q_d/\dot{m}c_p \tag{3}$$

The ECS subroutine operates in conjunction with the thermal analyzer program; at each iteration, the thermal analyzer program calls the ECS subroutine which calculates a new set of fluid temperatures. The fluid nodes which are coupled to equipment and structure are network boundary nodes, and their temperatures are calculated not by the thermal analyzer, but by the ECS subroutine. The subroutine uses the temperatures of the previous iteration for the components coupled to the fluid to calculate new fluid temperatures. In addition, heat exchange through active elements is calculated and transferred from the subroutine to the thermal analyzer network as an interface heat load.

ECS Modeling Using the Fluid Network Generator Program

FNG simplifies the set up of the ECS subroutine by writing the FORTRAN equations which represent the structural nodes coupled to the fluid and direct fluid heat loads. The analyst begins with an ECS schematic diagram and divides the loop into a series of individual fluid paths of constant flow rate. These paths are referred to as fluid branches. The analyst defines a fluid branch by assigning branch inlet and outlet nodes. These branch endpoints are called junction nodes.

Figure 1 depicts a simplified but complete ECS sample problem. The ECS loop is composed of series and parallel

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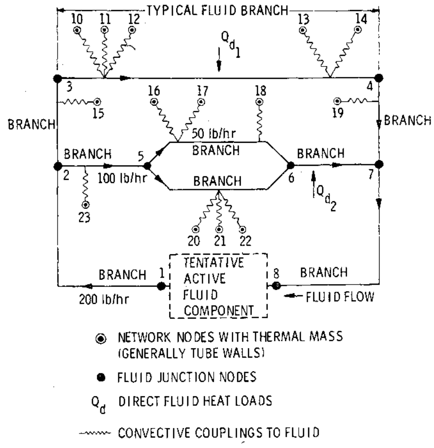

Fig. 1 Environmental control system sample problem.

combinations of fluid branches. Equations for the active thermal subsystems are added by the analyst who assigns junction fluid nodes for the inlet and outlet of the tentative active component to provide nodes necessary for the subsystem equations.

A fluid branch is described for the FNG with a set of cards which contain branch junction node identification, flow rate, network structural nodes coupled to the fluid loop, and direct fluid heat loads. The order in which the node structural couplings (nodes 10–23 in Fig. 1) and direct fluid heat loads (Q_{d_1} and Q_{d_2}) occur in the input data is identical with the order in which these parameters occur in the actual flow. Using this description, the FNG punches the basic fluid loop FORTRAN equations, using Eq. (2) to couple structural nodes to the fluid and Eq. (3) to represent direct fluid heat loads. The program assigns new fluid nodes and generates conductor numbers which connect structure to fluid. To complete the subroutine, the analyst writes equations for the active ECS thermal subsystems and calculates convective coupling values from structure to fluid using standard flow techniques. The FNG provides all required thermal network cards, so that the preliminary (no active components) thermal fluid subroutine can be used immediately.

The FNG Program is written in FORTRAN IV for CDC-6000 series computers and comprises 470 FORTRAN statements. A flow diagram is presented in Fig. 2.

Modeling of Active Thermal Subsystem Components

The technique required to model active ECS components is illustrated by deriving the equations for a typical water sublimator and gas-liquid heat exchanger. A water sublimator for a spacecraft environmental control system acts as a heat exchanger to remove excess thermal energy from the fluid and maintain the system at the required temperature level. The heat absorbed by a typical water sublimator is linearly related to the inlet fluid temperature,

$$Q_s = \dot{m}c_p\epsilon_s(T_I - 32) \tag{4}$$

A 32°F sink temperature is assumed. The outlet fluid temperature is then

$$T_O = T_I + Q_s/\dot{m}c_p \tag{5}$$

A gas-liquid heat exchange is used to maintain the cabin gas T_g, at the proper temperature by transfer of heat from the gas to the ECS. The heat transfer depends, of course, on the inlet gas temperature T_f and the inlet liquid temperature T_l. To determine T_f, the fan heat load is added to the gas flow, giving

$$T_f = T_g + Q_f/(\dot{m}c_p)_g \tag{6}$$

The liquid heat load is then,

$$Q_c = (\dot{m}c_p)_l\epsilon(T_f - T_l) \tag{7}$$

where ϵ represents the heat exchanger effectiveness. The net heat removed from the gas is

$$Q_n = Q_f - Q_c \tag{8}$$

This Q_n is transferred from the ECS subroutine to the thermal analyzer gas node. The thermal analyzer calculates the cabin gas temperature T_g, using this heat load.

The water sublimator and gas-liquid heat exchanger are represented in the ECS subroutine by Eqs. (4, 5, and 6–8), respectively. More complex active thermal subsystems such as astronaut coolant loops, radiators, and heat exchangers may be included with similar equations.

Model Restrictions and Limitations

The preceding steady-state equations neglect the thermal mass of the fluid and the transport time required for the fluid to flow around the loop. This is a valid approximation for vehicle information when the total thermal mass of the fluid for the system is small and transient effects are caused mainly by the thermal capacity of connected components. It is permissible to neglect the transport time when it is relatively short compared to the time required to change the equipment and structural temperatures significantly. The ECS subroutine may be used for both steady-state and transient vehicle analysis; for transient analysis the subroutine provides quasi-steady-state solutions as a substitute for actual transient response.

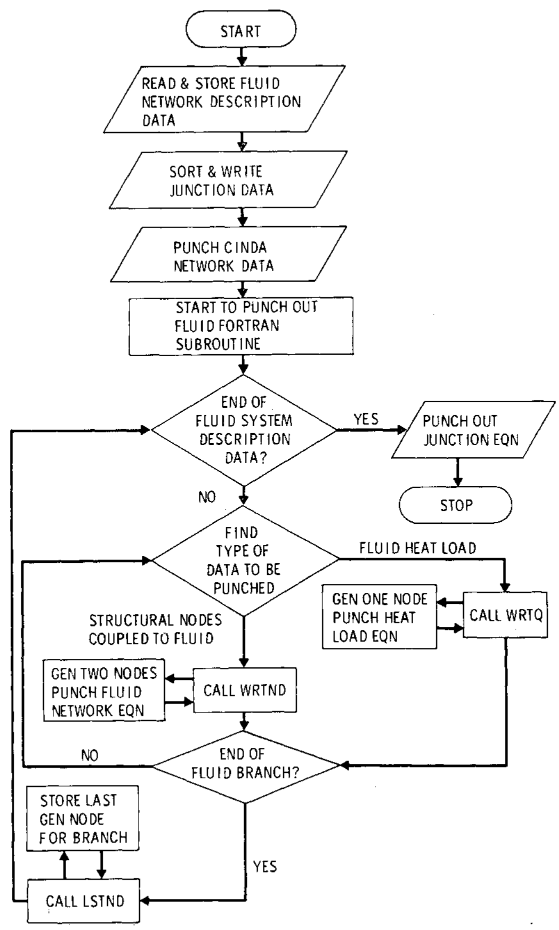

Fig. 2 Simplified flow diagram for the Fluid Network Generator.

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Water Impact Accelerations of Axially Symmetric Bodies

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Nomenclature

- F = Froude number, Eqs. (4)
- m = mass of body
- m_v = virtual mass of water
- v_0 = initial vertical velocity (impact velocity)
- v = vertical velocity
- h = displacement of body from free-water surface
- t = time after instant of contact
- ρ = mass density of water
- r = radius of body in plane of water surface
- R = radius of spherical bottom or characteristic length
- θ = semivertex angle of cone
- W = weight of body
- δ, τ = nondimensional length and time, Eqs. (4)
- μ = mass ratio, Eqs. (4)

Introduction

THIS study is concerned with the water impact of axially symmetric bodies. Water impact problems are important in some fields, especially in water-landing of seaplanes and of spacecraft. In 1929 von Kármán[1] derived the maximum impact loads of seaplane floats by applying the momentum theorem, and since then many investigations have been made for wedges entering the water surface. Studies of the water landing problems of spacecraft have been made recently at NASA Langley Research Center.[2,3] The object of these studies seems to have been to determine the practical design loads during the water impact of the particular spacecraft, and this objective was accomplished. However, they did not present the general formulas for the impact accelerations supported by systematic experiments.

This Note presents analytical and experimental results on impact accelerations of axially symmetric bodies landing on water. The formulas for the maximum impact accelerations are derived using the momentum theorem. The experimental results of spherical and conical models are presented and compared with the analytical results.

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Table 1 Spherical and conical models

Sphere	Radius, mm	Wt, kg A[a]	Wt, kg B[b]
S-1	239	1.429	1.399
S-2	203	1.374	1.344
S-3	156	1.300	1.270
Cone	**Semivertex angle, deg**		**Wt, kg**
C-1	65		1.530
C-2	60		1.383
C-3	55		1.349

[a] With a 100 g accelerometer.
[b] With a 200 g accelerometer.

Analysis

The original momentum of the body is assumed to be distributed between the body and the water during the impact.[1] From the momentum theorem the following equation can be written.

$$mv_0 = (m + m_v)v \tag{1}$$

The body considered has the axially symmetric bottom surface. We propose that the virtual mass for axially symmetric body be taken equal to one-half the virtual mass of a circular plate having a diameter equal to the instantaneous diameter of the body in the plane of the water surface. The virtual mass of the circular plate is given by Lamb[4] as

$$m_v = \tfrac{8}{3}\rho r^3 = (2/\pi)(\tfrac{4}{3}\pi\rho r^3) \tag{2}$$

For the spherical bottom surface, the virtual mass can be written as

$$m_v = \tfrac{4}{3}\rho h^{3/2}(2R - h)^{3/2} \tag{3}$$

The following nondimensional parameters are now introduced:

$$\delta = h/R,\ \tau = gt/v_0,\ F = v_0/(gR)^{1/2},\ \mu = 3W/4\pi\rho g R^3 \tag{4}$$

Substituting Eq. (3) into Eq. (1) gives

$$d\delta/d\tau = \mu F^2/[\mu + \delta^{3/2}(2 - \delta)^{3/2}/\pi] \tag{5}$$

If $\delta \ll 1$, Eq. (5) is easily integrated to yield

$$\tau = (\delta/\mu F^2)\ [\mu + (2^{5/2}/5)(1/\pi)\delta^{3/2}] \tag{6}$$

The acceleration can be calculated as

$$d^2\delta/d\tau^2 = -[3 \times 2^{1/2}\mu^2F^4\delta^{1/2}/\pi(\mu + 2^{3/2}\pi^{-1}\delta^{3/2})^3] = -F^2n \tag{7}$$

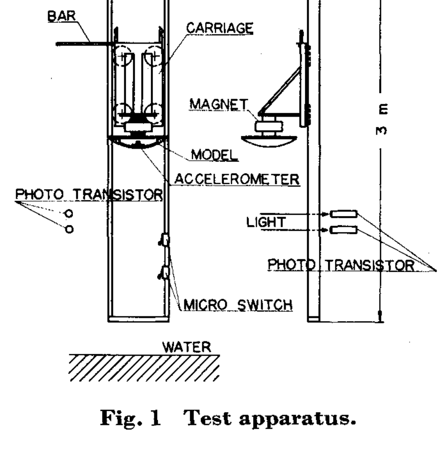

Fig. 1 Test apparatus.