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Spacecraft Heat Transfer Analysis

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INTRODUCTION

Two somewhat related but yet distinct topics are presented below. First, some of our thoughts, at the Jet Propulsion Laboratory, on the position of computing as a tool for developing the thermal design of a spacecraft are given. The purpose in doing this is to stimulate discussion on the subject of the computer by presenting one approach to how computing might fit into thermal design. Second, a new general type heat transfer program that was recently acquired from Arthur D. Little, Inc. is briefly described. The program is called, "The Method of Zones for the Calculation of Temperature Distribution."

DISCUSSION OF COMPUTING

Over the past few years - actually from the early days of the Jet Propulsion Laboratory's involvement in space projects - those who have been close to spacecraft thermal control, directly or indirectly, have been concerned over the position that the digital computer should hold in the overall effort of spacecraft thermal design.

There is a general awareness of the importance of the digital computer and of analysis, in general, in a thermal design effort. At the same time, it is also very clear that analysis and, in particular, complicated analysis involving the digital computer is not precise, and therefore, cannot be relied upon by itself to establish the final thermal design of a spacecraft. Solutions obtained from the digital computer are simply not accurate enough, or at most, our confidence in their accuracy is not sufficient, for them to be the sole basis of final design certification. Collaboration of the experimental and the analytical is essential to establish confidence in the suitability and reliability of a design. Nevertheless, the computer, in spite of its shortcomings, does appear to have great potential, perhaps more potential than any other single tool available to the temperature control engineer.

The usual technique for using computers to solve complicated heat transfer problems is to lump into nodes, zones, and so forth, incremental volumes to form a network analog or model of the heat flow paths present in the physical problem. The computer, of course, then analyzes this computational model. This is fine; but in the process of transcribing a real problem into a computational model, the important question arises of how well this process can be carried out for very complicated problems, and consequently, how much confidence can be placed in computed data?

The difficulties encountered in computational modeling can probably be considered as arising from two sources; the modeling of the heat flow paths present in the hardware, and the assigning of numerical values to describe the lumps and the interactions between lumps. For geometrically simple problems, the lumping or formation of a heat flow model is a relatively straightforward process with most computer programs having analytical guide lines. However, when the geometry of a problem is complicated, computational modeling becomes difficult and simple analytical guide lines become almost meaningless. The lumping process becomes partly intuitive and accurate representation becomes heavily dependent upon engineering understanding, judgement, and experience. This leads to uncertainties and a corresponding lack of confidence in computed results. In the area of assigning numerical values to describe the lumps and their interactions, the main problem is of a different nature and centers around obtaining reliable thermo-physical data; for example, obtaining reliable joint conductance information. Problems in this area will certainly diminish as a result of current and future thermo-physical research.

In addition to those problems associated with the modeling of hardware, uncertainties are also introduced because of the equations upon which we base our calculations; for example, it is known that the physical idealizations which are generally ascribed to the behavior of radiation interchange are very liberal. This type of uncertainty will also diminish with future research on the physical behavior of heat transport. The last type of error which is encountered in computed data results from numerical inaccuracies in computation; however, this type of error can be controlled since it is mathematical in nature, involving numerical analysis.

Faced with uncertainties of the type just described, it is legitimate to question the possible usages of the digital computer in thermal design and, of course, the consequential advantages of its utilization.

In reviewing the development scheduling of a spacecraft, it appears that the use of the computer should be initiated as early as possible. Certainly, it should be initiated no later than the completion of preliminary design when mission objectives and general spacecraft configurations are somewhat defined in terms of probable size, shape, power, and so forth. The purpose would be to investigate, as early as possible, the feasibility of preliminary design concepts as they relate to a particular spacecraft's configuration and mission. The results from such early analytical investigations do not have to be very accurate or very detailed; all that would be sought is verification that preliminary design concepts do indeed produce desired trends. For example, suppose that preliminary estimates call for a particular type of temperature control hardware such as louvers; it certainly would be desirable to analytically verify, early in the development schedule, that the louvers are really needed and, if so, that they produce the desired degree of control. Furthermore, and perhaps just as important, it would be very desirable to know early in design the criticality of such a device to parametric, thermal variations so as to know what conditions lead to marginal and unreliable operation. Early analytical investigations in which complicated spacecraft thermal interactions are accounted for, offer the opportunity of uncovering critical thermal problems so as to allow a maximum of time for their solution or to permit alterations in configuration and/or mission objectives with the least amount of disturbance. It should be pointed out that such early investigations can only be carried out analytically since experimental hardware is not available, and that only through the use of the computer can the necessary sophistication be brought to bear; by this is meant the multiplicity of thermal interactions. Further development in the methodological use of the digital computer must be carried out in order that such early investigations can be performed with reasonable confidence.

Upon confirmation of preliminary design concepts and corrections thereof, the simple computational models used can then be refined to conform more and more closely with actual spacecraft hardware in order to perform detailed thermal investigations. However because of the uncertainties associated with computer analysis, it is essential that refinements in computational modeling be carried out in conjunction with experimentation. The inclusion of the experimental with the analytical forms an iterative process or procedure. With somewhat refined computational models, parametric studies can be undertaken to determine the importance of various thermal elements making up the model. For example, the thermal influence of a particular joint thought to be important could be analytically studied to determine its influence. If found to be important, an experiment could be developed to determine fairly precisely the magnitude of the conductance across the joint. The experimental result would then be incorporated into the computational model. This sort of iteration procedure can be repeated, using the computational model itself to determine its own shortcomings through parametric study, until a fairly representative model evolves in the sense that the heat transfer within a piece of hardware is well understood. Utilization of the computer in this manner aids in directing and giving credence to certain test programs; that is, it aids in determining just what areas are really important to test. Verification of the computational model of course requires experimental correlation of its ability to predict steady-state and simple transient conditions. Once correlation has been established, it would then be possible to investigate all thermal events occurring during the course of a mission, which is something that is entirely impractical to carry out experimentally. Another thing that is impractical experimentally, but easily done analytically, is failure mode studies in which various possible failures can be studied to determine their effect.

The potential advantages of better integrating the digital computer into the design effort lie basically in obtaining concrete design information at an earlier time in the over-all development schedule. Without analysis upon which we can place a high degree of confidence, concrete design information must necessarily wait for hardware development, fabrication, and delivery before experimental information can be obtained. Design changes at this point can only be justified when catastrophic failure or unsolvable situation is expected. Thus, the temperature control engineer must live with his problem with little or no chance of sidestepping it through hardware redesign. What we are seeking in temperature control is earlier decision capability in order to better integrate thermal considerations into other aspects of hardware design. To do this, we must be able to obtain thermal information, accurately founded, at a pace consistent with other design activities. There appears to be no way, other than analysis.

Current plans are to investigate possible ways in which the digital computer can best be used within the framework of its current uncertainties. A particular configuration will be analyzed in order to define the difficulties encountered in using the computer and to find ways around these difficulties. In this investigation, testing will be used as a complement to analysis in the manner described previously. The object for analysis will be the Arthur D. Little thermal scale models. The ADL models have been thoroughly tested and the accuracy of the results is almost unquestionable. Plans call for using the computer along with complementary testing to predict the thermal condition of the models. For this effort, none of the ADL model test results will be used as inputs for analysis. They will be used only as a standard for comparison with analytically obtained predictions. In this way, it is planned that ways of sidestepping some current uncertainties in analysis will be found. This will in turn lead to ways of better exploiting the potential of the computer.

METHOD OF ZONES

Next, a new heat transfer program which was recently acquired from Arthur D. Little, Inc. and which is called, "The Method of Zones for the Calculation of Temperature Distribution," will be described. There are two reports on this program, so the description will be brief. The first report covers the methodology of the approach used in the program. The second part is a description of how to use the program covering the input and output format and a program listing.

The "Method of Zones" is an improved method for obtaining solutions to spacecraft associated heat transfer problems involving radiation and conduction. The program is one of the few general type heat transfer programs specifically designed for spacecraft heat transfer problems. The approach used in the program is not that of simply lumping parameters to form a nodal network analogous to an electrical circuit as in most general heat transfer programs. Rather, the approach consists of breaking a problem into zones of finite area for two-dimensional situations and into finite volumes for three-dimensional situations. The approach retains the essential characteristics of boundary value techniques in that each zone is characterized by prescribing conditions to the boundaries of each zone. The boundary conditions can represent a known heat input or output rate, or an unknown heat input or output rate expressed in terms of an unknown boundary temperature function such as T^4. The generalized heat diffusion equation is written for each zone and is integrated over the volume of the zone. The integration is performed by introducing the volumetric mean temperature of the zone. The integration of the diffusion equation results in an instantaneous heat balance equation which involves the heat fluxes over the boundaries of the zone and the rate of change in the mean temperature of the zone; that is, we have a differential equation expressed in terms of the time rate of change in mean temperature and the heat fluxes over the boundaries. The differential equation itself is no different than one would find in the typical lumped parameter program. The difference results from relating the input and output fluxes in the differential equation to the boundary conditions of the zone. This is done by deriving approximate formulas, based upon an assumed parabolic temperature distribution in the zone, in which the fluxes at the boundaries are expressed in terms of the boundary's mean temperature and the zone's mean temperature. If the boundary conditions are ignored, the program degenerates into the typical lumped parameter program. Each zone is, thus, mathematically characterized by a set of equations consisting of one differential equation for the mean temperature of the zone and a number of boundary equations (algebraic) for the temperature of the boundary. The equations are solved in a manner normal to other general heat transfer programs in that the differential equation is solved implicitly; however, the boundary equations are solved explicitly. The higher order of approximation resulting from the parabolic assumption permits a complicated system to be subdivided into fewer parts than is necessary when conventional methods are used.

In the report on the program, three simple examples are given to illustrate the application and accuracy of the method. Criteria are also given which enable zone sizes to be chosen properly in practical applications. The criteria are derived by comparing calculations made by the method of zone with exact results obtained for simple cases.

The numerical procedure, which is a modified Gauss-Seidel procedure, for solving the difference equations at each time step is discussed, and experience by ADL with convergence of the procedure is reviewed. The program also includes checking procedures which are based on the principles of reciprocity and conservation of energy. These provide an initial check on the consistency of the input through the reciprocity principle, and a running check on the solution of a problem through the conservation of energy principle. Capability is built into the program and is controllable by the user for stopping the computer should the conservation of energy check show that the numerical solution is not being carried out to desired accuracy.

As far as the user is concerned, the input and output formats of the program are as simple as any the writer has seen. However, all information supplied to the program must be supplied in duplicate in order that the reciprocity principle can check for input consistency. One of the important advantages in the program results from the way the equations are written. Being written in terms of flux instead of temperature, permits the utilization of Oppenheim's network method for diffuse inter-reflections or Bobco's corollary for specular inter-reflections involving planar surfaces.