MODELLING OF TRANSIENT TESTS TO DETERMINE THERMAL PROPERTIES OF FIBERGLASS INSULATIONS

J. R. Thomas

Mechanical Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

ABSTRACT

Transient test methods for fibrous insulations require a sophisticated analysis technique because of the more rapid response of radiation heat transfer as compared to conduction, and because of the interaction between the two modes. A high-order combined-mode heat transfer model has been developed for this purpose, and benchmarked against experimental results. The model is capable of reproducing the experimental data to within 1.2°C throughout the duration of a transient test when the sample specific heat is corrected for moisture content. The model has yielded several interesting insights into transient testing techniques.

INTRODUCTION

Transient test methods have recently been introduced [1-4] to determine the thermal resistance and conductivity of thermal insulations. Such methods offer the potential for considerable savings as compared to steady-state methods, since the long wait for steady conditions may be avoidable. These methods also introduce some challenging questions for thermal analysts, however, particularly for low-density fibrous insulations in which radiation is known to make a considerable contribution to the total energy transfer [5]. Since radiation propagates at the speed of light, the early stages of a transient test are likely to be dominated by radiative transfer, possibly leading to misleading results for the conductivity. Attempts to analyze the results of such experiments with independent calculations of radiative and conductive components or with low-order models have not been totally successful, so a more sophisticated approach was considered necessary. The problem is complicated by the interaction of radiation and conduction through the absorption and re-emission of radiant energy, and by the highly anisotropic scattering properties of glass fibers [6].

The model to be described below was developed as an attempt to account for these effects. Coupled radiative-conductive heat transfer is accounted for through a simultaneous solution of the equation of radiative transfer and the energy equation [7]. The anisotropic scattering kernel is represented by a 20-term Legendre polynomial expansion and the
The equation of transfer is solved by a high-order \( P_N \) approximation [9]. The energy equation is solved by implicit finite differences.

**ANALYSIS**

The specific objective of the project was to develop a model for the flat-screen test apparatus at Oak Ridge National Laboratory (ORNL) [10]. This system is shown schematically in Figure 1. It consists of a screen wire heater (labelled "hot boundary") of thickness \( l \), the insulation specimen of thickness \( L \), and the cold boundary, which is formed of a thick slab of copper to enforce isothermal conditions. A typical experiment proceeds as follows [3]: The system begins at a uniform equilibrium temperature; at time \( t = 0 \) a constant voltage is applied to the screen, producing a current and corresponding heat generation at the rate \( q \). Thermocouples attached to the screen monitor its temperature, and an average value is logged every 30 or 60 seconds. This continues until the screen reaches a new equilibrium temperature.

**Problem Formulation**

It is assumed that the heating element may be represented by a lumped-capacitance model in which energy is generated by the electrical current at the rate \( q \) (\( W/m^3 \)). The screen loses heat by conduction and radiation into the specimen, and gains heat by radiation from the specimen. Thus an energy balance on the screen yields [4]

\[
\rho_h c_h \frac{dT_h}{d\xi} = \frac{d}{dx} \left[ q + k \frac{dT}{dx} \right]_{x=0} - \varepsilon_h \sigma T_h^4 + \alpha_h q_r , \tag{1}
\]

in which \( T_h \) represents the screen (hot boundary) temperature, \( \rho_h \) and \( c_h \) its density and specific heat, and \( \varepsilon_h \) and \( \alpha_h \) the total emissivity and absorptivity of the screen surface, respectively. The symbols \( k \) and \( T \) represent the thermal conductivity and temperature of the insulation, so that the term \( k \frac{dT}{dx} \bigg|_{x=0} \) represents conduction away from the screen. \( \xi \) represents time and \( q_r \) the radiative flux incident on the screen from the medium.

Within the insulation specimen, we have heat transfer by combined radiation and conduction. Thus \( T(x,\xi) \) satisfies the equation [7]

\[
k \frac{d^2 T}{dx^2} - \frac{d q_r}{dx} = \rho_p c_p \frac{dT}{d\xi} , \tag{2}
\]

where \( \rho_p \) and \( c_p \) are the density and specific heat of the insulation, and \( q_r \) is the radiative flux. The radiative flux is computed from the radiation intensity \( I(x,\mu) \), where \( \mu \) is the direction cosine, according to [7]*

\[
q_r(x,\xi) = 2\pi \int_{-1}^{1} I(x,\mu) \mu d\mu . \tag{3}
\]

*The time dependence of \( I(x,\mu) \) is suppressed in the notation since it is only parametric. See Ozisik [7], p. 252.