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Convection-radiation from a continuously moving, variable thermal conductivity sheet or rod undergoing thermal processing

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ABSTRACT

A numerical study of the heat transfer process in a continuously moving sheet or rod of variable thermal conductivity that loses heat by simultaneous convection and radiation is reported. The process is governed by five dimensionless parameters, namely Peclet number Pe, thermal conductivity parameter a, convection-conduction parameter N_c, radiation-conduction parameter N_r, and sink-to-base temperature-ratio, θ_a. The effects of these parameters on the temperature distribution, base heat conduction rate, advection and surface heat loss are illustrated and explained. The dimensionless length parameter, L^*, that the material must traverse to cool to within one percent of the sink temperature is determined for various combinations of the five parameters. This information gives the designer the fabrication time if the material is moved at a certain speed or it gives the speed if the processing of the material is to be completed in a fixed period of time.

1. Introduction

In processes such as extrusion, glass fiber drawing, hot rolling and casting, the material being manufactured is processed thermally by allowing it to exchange heat with the ambient while it is in continuous motion [1–8]. The purpose of the thermal treatment is to cool the material to a desirable temperature before it is spooled or removed. The velocity of the material can be extremely low (few centimeters per hour) such as in crystal growth or very fast (few meters per second) as in optical fiber drawing. As the material at high temperature emerges from a furnace or a die, it is exposed to the colder ambient and a transient conduction process accompanied by surface heat loss is initiated. For the slow-moving material, the initial transient dies out with the passage of time and the process quickly attains a steady state. However, for a fast-moving material, the temperature distribution may continue to evolve with time during the entire duration of thermal processing.

Studies of fluid flow and heat transfer from a heated moving surface may be classified into three groups. The first group comprises of papers in which the fluid flow over the surface is assumed to be either induced by the motion of the surface in an otherwise quiescent fluid or the flow is driven by an independent source. Assuming a specific thermal boundary condition at the surface, the applicable continuity, momentum and energy equations are solved to obtain the velocity and temperature fields in the fluid. The final outcome is the surface heat transfer data such as the convection heat transfer coefficient. This group of papers does not address the problem of thermal transport in the moving material itself. The number of papers belonging to this group is vast, covering Newtonian and non-Newtonian fluids, surface mass transfer, magnetic and electric effects, different thermal boundary conditions, combined free and forced convection, etc. References [9–12] provide a representative sample of such studies chosen from the recent literature.

The second group of papers considers the thermal transport in the fluid and in the moving material concurrently and treats the process as a conjugate conduction-convection process. Karwe and Jaluria [13] considered the flow field generated due to the movement of a continuous heated surface and used the Crank–Nicolson finite difference method to compute the temperature fields in the fluid and in the moving material. They also derived analytical solutions for the situation when the surface convection heat transfer coefficient is known a priori. This work was later extended to include buoyancy effects in the flow field induced by the motion of heated surface, i.e., a mixed convection situation [14,15]. As expected, the effect of buoyancy was found to be more significant

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