HEAT TRANSFER

KOREA-U.S. SEMINAR ON THERMAL ENGINEERING AND HIGH TECHNOLOGY

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HEAT TRANSFER: KOREA–US SEMINAR ON THERMAL ENGINEERING AND HIGH TECHNOLOGY

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Preface

Heat transfer is important in many industry applications. It will continue to play a vital role as much modern equipment is required to be more compact, strong, durable, and heat-resistant without compromising overall performance. Thermal limits often impose a design limit on heat exchangers, micro-electronic equipment, power plants, propulsion systems, and many other industry systems. The need to manufacture high-temperature, high-performance materials for aerospace and combustion systems, to develop improved cooling technology for semiconductor devices, to increase thermal efficiency of power systems, and to manage and conserve energy more efficiently, to name a few examples, will continue to spur added interest in heat transfer.

This volume contains lectures and papers presented at the Korea–U.S. Joint Heat Transfer Seminar held in Seoul, Korea, October 16–22, 1986. The seminar was jointly sponsored by the Korea Science and Engineering Foundation (KOSEF) and the U.S. National Science Foundation (NSF). The objectives of the seminar were; to exchange current information on science, art, and technology in heat transfer, to promote scientific cooperation between the heat transfer communities of both nations, and to provide an opportunity for individual participants to explore developing possible joint research programs in topics of high priority and mutual interest to both countries. The seminar provided an excellent forum for reviewing progress of the past and needs for the future in heat transfer technology for the two nations. The theme of the seminar was heat transfer in thermal engineering and high technology systems. The scope, however, was deliberately left broad and general as the seminar earmarked the first formal scientific exchange between Korea and the United States in the area of heat transfer. The topics covered were thus diverse and comprehensive; ranging from scientific fundamentals to engineering applications in both conventional and high technology systems.

It is envisioned that these proceedings will contribute to the advancement of the art and science of heat transfer and further stimulate interest in this exciting area. It is also hoped that scientific cooperation will continue to develop between the heat transfer communities of both nations, in much the same spirit and tradition as the friendly and cooperative efforts demonstrated in numerous other areas between the two countries.

Jong Hyun Kim
Sung Tack Ro
Taik Sik Lee

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Jong Hyun Kim
Sung Tack Ro
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Thermal Instability in a Horizontal Fluid Layer Cooled from Above

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1. INTRODUCTION

The onset of thermal convection in an initially quiescent, horizontal fluid layer with a linear decrease in the top surface temperature was investigated theoretically by Foster [1] in 1965. Assuming some initial conditions and their amplification, he tried to clarify the onset of manifest convection. His predictions agree well with experimental results, providing the amplification ratio of 10 to 10^8 for each set of data [2-4]. The uncertainties about the initial conditions and the amplification factor have been reported [5-8]. Jhavery and Homsy [9] analyzed this problem, using a stochastic model that the critical time of manifest convection would be the moment when the Nusselt number exceeds the value of 1.01. All these models require the experimental data in describing the conditions of the onset. The validity of this initial value approach is clouded, because the initial conditions are not clear.

Choi, Yeo, Kwon and Yoo [10] analyzed the above stability problem, assuming that for large Prandtl numbers the temperature disturbances are initiated within the conventional thermal penetration depth of conduction. The predicted results of the time of the onset based on the quasi-static model are located between those from the amplification theory and experiments reported by Kaviany [4]. Their quasi-static model seems rather reasonable, but it is restricted to the case of very large Prandtl numbers.

Very recently Yoo and Choi [11] reformulated the stability equations for the present problem by employing the propagation theory. This linear theory was applied to the system of plane Couette flow with success by Choi, Shin and Hwang [12]. For the present system this theory requires that the initiated disturbances at the time of the onset of motion follow the principle of exchange of stabilities but time-dependently. Yoo and Choi's predictions for large prandtl numbers were almost the same as those from the modified quasi-static model.

The object of the present study is to predict the time of the onset of convection by applying the propagation theory to the above stability problem for the case of extremely small Prandtl numbers and therefore to elucidate the effect of the Prandtl number to a certain degree. Therefore the present report complements the work of Choi, Yeo, Kwon and Yoo [10] and also Yoo and Choi [11].

2. AMPLITUDE EQUATIONS

2.1 Description of the System

The system considered here is an infinite horizontal layer of Newtonian fluid cooled from above by decreasing the temperature of the upper surface at a constant temporal rate β. The fluid layer placed between two rigid plates is kept at the constant temperature T_0 for time $t \leq 0$, but its upper surface temperature decreases by βt for $t \geq 0$. Figure 1 gives a schematic of the system.

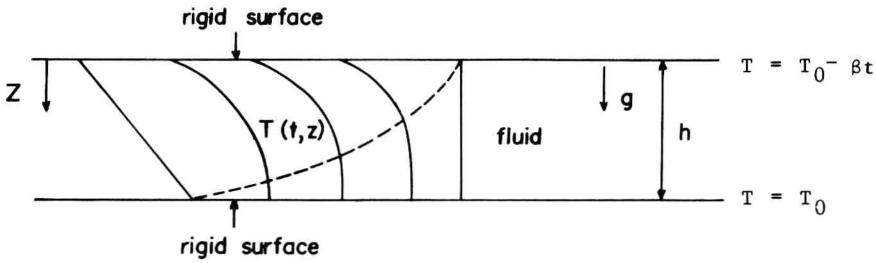

FIGURE 1. A schematic diagram of the system

The basic temperature profile due to conduction is easily obtained and its exact solution is well known [1]. But it brings the mathematical difficulty in conducting the stability analysis. For the present system the following approximate solution from the integral method is known to be very useful for $\tau \geq 0$:

$$\theta_0 = -\tau(1-\zeta)^5 \qquad \text{for} \qquad 0 \leq \zeta \leq 1 \qquad (1)$$

$$\theta_0 = 0 \qquad \text{for} \qquad 1 \leq \zeta \leq 1/\delta \qquad (2)$$

where $\theta_0 = \kappa(T-T_0)/(\beta h^2)$, $z=Z/h$, $\tau = t\kappa/h^2$ and $\zeta = z/\delta$. δ is the dimensionless thermal penetration depth and κ denotes the thermal diffusivity. The above solution satisfies all the initial and boundary conditions for deep-pool systems and agrees well with the exact solution in the range of $\tau \leq 0.3$. For the present system δ is found to be $(20\tau)^{\frac{1}{2}}$ from the conservation law of energy.

When the cooling rate is very high, thermal convection will set in at a critical time τ. The problem is to find the critical time marking the onset of convection due to buoyant forces for a given cooling rate and the Prandtl number. Of particular interest are the critical conditions for a deep-pool system satisfying equations (1) and (2).

2.2 Formulation of Amplitude Functions

For the present system the perturbation equations to describe disturbances caused by thermal convection is well known [1,4]. The equations are formulated by assuming the quantities of disturbances extremely small under the Boussinesq approximation. Since there are no lateral boundaries on the system, an arbitrary disturbance in the xy-plane is expressed in terms of two-dimensional periodic waves having the horizontal wave number 'a'. By applying the linear stability theory the dimensionless governing equations are generated as

$$\left\{\frac{1}{Pr}\frac{\partial}{\partial\tau} - \left(\frac{\partial^2}{\partial z^2} - a^2\right)\right\}\left(\frac{\partial^2}{\partial z^2} - a^2\right)w = a^2\theta \qquad (3)$$

$$\left\{\frac{\partial}{\partial\tau} - \left(\frac{\partial^2}{\partial z^2} - a^2\right)\right\}\theta = -Ra\frac{\partial\theta_0}{\partial z}w \qquad (4)$$

where w represents the amplitude function of vertical component of velocity perturbation and θ the temperature perturbation. Ra denotes the Rayleigh number and Pr the Prandtl number. The boundary conditions for rigid surfaces are given by

$$w = \frac{\partial w}{\partial z} = \theta = 0 \quad \text{at} \quad z = 0 \quad \text{and} \quad z = 1 \qquad (5)$$

Based on these equations, a minimum value of the Rayleigh number and its corresponding wave number should be sought for a given Pr and τ.

In the conventional quasi-static models the time-dependent terms are neglected. The amplification theory employs some initial conditions at $\tau = 0$ and their transient behavior is traced until the magnitude of the velocity disturbance grows by 1000 times its initial value. Since each model has its own lack of validity, the stability analysis is conducted by applying the propagation theory. For this purpose the similarity variable ζ is used, based on the length scaling factor δ. By introducing the transformed function $w^*(\zeta) = w/\delta^2$, all the governing equations can be reformulated as a function of only ζ as follows:

$$(D^2 - a^{*2})\left\{(D^2 - a^{*2}) + \frac{10}{Pr}(\zeta D - 2)\right\}w^* = -a^{*2}\theta^* \qquad (6)$$

$$(D^2 + 10\zeta D - a^{*2})\theta^* = Ra^*(D\theta_0)w^* \qquad (7)$$

where $D = \frac{d}{d\zeta}$, $a^* = a\delta$ and $Ra^* = Ra\,\delta^3$. Now, it is shown that the parameters to determine the stability criteria are Pr, $Ra^*\tau$ and a^* for a deep-pool system. The relationship of $Ra^*\tau$ = constant means that the critical time will be inversely proportional to the two-fifth power of the Rayleigh number. This trend coincides with the extant theoretical predictions [1,4,9]. In solving these amplitude equations no further assumption is needed except the principle of exchange of stabilities. This is the essence of the propagation theory introduced by Choi, Shin and Hwang [12].

3. SOLUTION PROCEDURE

The earlier studies have been primarily concerned with the case of very large Prandtl numbers. Its detailed solution procedure is described in the work of Yoo and Choi [11], which is similar to the present one. Since the present work concerns the case of extremely small Prandtl numbers, the governing equations can be simplified to

$$\{10(D^2 + 10\zeta D - a^{*2})(D^2 - a^{*2})(\zeta D - 2) + PrRa^*\,a^{*2}(D\theta_0)\}w^* = 0 \qquad (8)$$

This simplification means that in the case of $Pr \to 0$ the viscous effects are neglected and the important parameters are found to be $PrRa^{*}\tau$ and a^{*}. Note that the order of differentiation is reduced to a fifth order. Since viscous effects prohibit a fluid from slipping along a solid boundary, the condition of no tangential slip at the upper boundary is relaxed by removing the boundary condition of $\partial w/\partial z = 0$ at $z = 0$ in equation (5). For a deep-pool system $z = 1$ corresponds to $\zeta \to \infty$

Now, the inner solution w_i^* for $\zeta \leq 1$ is obtained by applying the Frobenius method:

$$w_i^* = \sum_{n=0}^{\infty} b_n \zeta^{n+s} \tag{9}$$

By substituting equation (9) into equation (8), the indicial equation and the solution to satisfy all the upper boundary conditions are obtained as

$$s(s-1)(s-2)^2(s-3) = 0 \tag{10}$$

$$\begin{aligned} w_i^* &= H_1\{\zeta - \frac{1}{360}(\frac{1}{2} Pr\, Ra^{*}\tau\, a^{*2} + 10 a^{*2} - a^{*4})\zeta^5 + \ldots\} \\ &+ H_2\{\zeta^2 - \frac{1}{2880} Pr\, Ra^{*}\tau\, a^{*2}\zeta^6 + \ldots\} \\ &+ H_3\{\zeta^3 - \frac{1}{30}(5 - a^{*2})\zeta^5 + \ldots\} \end{aligned} \tag{11}$$

where the coefficients H_i $(i = 1,2,3)$ are the arbitrary constants.

The outer solution w_o^* in the range of $1 \leq \zeta \leq 1/\delta$ with $\delta \to 0$ would not be obtained easily. Therefore, its homogeneous solution $w_{o,h}^*$ is produced from equation (6) for $Pr \to 0$ as follows:

$$w_{o,h}^* = \frac{H_4}{2}\{(1 - a^{*}\zeta)e^{-a^{*}\zeta} + a^{*2}\zeta^2 \int_{\zeta}^{\infty} \frac{e^{-a^{*}x}}{x} dx\} \tag{12}$$

The solution of θ_0^* is generated by using the WKB method and it is transformed in the forms of $\exp(a^{*}r)p(r)$ and $\exp(-a^{*}r)q(r)$. $p(r)$ and $q(r)$ are the power-series forms as the function of $r = \zeta - 1$. Then equation (8) can be written through the operator technique as

$$(r+1)D^{*}w_o^{*} - 2w_o^{*} = \frac{H_5}{2a^{*}}(e^{a^{*}r}\sum_{n=0}^{\infty}\frac{b_n}{n+1}r^{n+1} - e^{-a^{*}r}\sum_{n=0}^{\infty}\frac{c_n}{n+1}r^{n+1}) \tag{13}$$

with $b_0 = c_0 = \theta_0^*(1)$, $b_1 = D\theta_0^*(1) - a^{*}\theta_0(1)$ and $c_1 = D\theta_0^*(1) + a^{*}\theta_0^*(1)$. D^{*} indicates the differentiation with respect to r. The values of θ_0^* and $D\theta_0^*$ at $\zeta = 1$ are obtained from the WKB solution and the recursion formula for b_n and c_n can be easily constructed. The particular solution is obtained in the form of

$$w_{o,p}^* = e^{a^{*}r}\sum_{n=0}^{\infty} d_n r^n + e^{-a^{*}r}\sum_{n=0}^{\infty} e_n r^n \tag{14}$$

where the constants d_n and e_n are easily determined from equation (13) with $d_0 = d_1 = e_0 = e_1 = 0$. Now the outer solution can be obtained as $w_o^* = w_{o,h}^* + w_{o,p}^*$.

Since the solution to satisfy all the boundary conditions is found in the whole domain, the secular equation to characterize the onset of convection is generated by using the following interface conditions as usual [11]:

$$D^n w_i^* = D^n w_o^* \quad \text{at} \quad \zeta = 1 \tag{15}$$

with n = 0,1,2,3,4. From the resulting equation in the form of the (5 X 5) square matrix the value of $Pr Ra^* \tau$ is obtained for a given a^*. The minimum value of $Pr Ra^* \tau$ in the plot of $Pr Ra^* \tau$ vs. a^* is the critical condition to mark the onset of thermal convection.

4. RESULTS AND DISCUSSIONS

The predicted onset conditions for $Pr \to 0$ are found:

$$(Pr Ra^* \tau)_c = 1762 \quad \text{and} \quad a^* = 4.20 \tag{16}$$

where the subscript c indicates the critical state. Since $\delta = (20\tau)^{\frac{1}{2}}$, the onset time can be expressed as

$$\tau_c = 3.29\,(Pr Ra)^{-2/5} \quad \text{and} \quad a_c = 0.517\,(Pr Ra)^{1/5} \quad \text{for} \quad Pr \to 0 \tag{17}$$

This relationship is almost the same as that in the work of Yoo and Choi [11]. Their values of the coefficients in equation (17) were 3.32 and 0.577, respectively, under the assumption that all the disturbance quantities will be confined within the thermal penetration depth.

The profiles of amplitude functions are illustrated in normalized forms in Figure 2. The profile of temperature disturbances is found to show almost the same trend with those of $Pr \to \infty$ in the work of Yoo and Choi [11]. Therefore it may be stated that temperature disturbances will be initiated within the thermal penetration depth of conduction in the whole range of the Prandtl number without the loss of generality. But this generality cannot be generated for velocity disturbances. As the Prandtl number increases, the velocity disturbances will be progressively penetrated to a deeper depth over the thermal penetration depth. This effect will make the system more unstable. Finally the onset time will lead to the following relation:

$$\tau_c = 4.36\ Ra^{-2/5} \quad \text{and} \quad a_c = 0.29\,Ra^{1/5} \quad \text{for} \quad Pr \to \infty \tag{18}$$

which is independent of the Prandtl number.

For a deep-pool system, it is certain that as the Prandtl number increases, the onset time will become smaller for a given Ra. Based on these studies, the critical criteria may be roughly constructed as

$$\tau_c Ra^{2/5} \cong 3.29\ (2.02 + 1/Pr)^{2/5} \tag{19}$$

The critical wave number may have the relation:

$$a_c Ra^{-1/5} \cong 0.517\ (18.0 + 1/Pr)^{-1/5} \tag{20}$$