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STUDY OF THE PRANDTL NUMBER IN TURBULENT FLOW OF AIR WITH INJECTION AND SUCTION

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ABSTRACT

The main purposes of a Heating, Experimental values for Pr (0.71) have been obtained from the mean velocity and temperature profile data of Simpson [5] and Whitten [6] for various condition like blown, unblown, and sucked turbulent incompressible air in above mentioned boundary condition. The value of Pr no. lies in the range of 1>Pr>1, means forinner similarity region, Pr< 1 while ***Pr***>1 in the outer similarity region.These results are in agreement with Ludwieg's [2] pipe results and show no effect of blowing or suction on ***Pr*,.** The Jenkins model [21] is found to describe the variation of Pr, which accounts for the unequal loss of momentum and thermal energy from an eddy in Sight for Pr = 1 fluids in the inner region within experimentaluncertainty of the data. Also using Hinze'ssuggestion that the diffusion of heat might be a combination of gradient and large eddy transport, a new model is developed to account for Pr< 1 in the outerregion. Predictions based on these models lie within the uncertainty band of the experimental results and indicate no effect of blowing or sucking on ***Pr***.

Keywords*:* Pr No., Turbulent flow, Suction and injection.

I. INTRODUCTION

The primary requirement of As IS well known, there exists at the present timeno purely theoretical solution of the fluiddynamics of the turbulent boundary layer.Consequently there is no theoretical solutionavailable for heat transfer in the turbulentboundary layer. In the momentum problem the"eddy viscosity" remains unknown while the"eddy conductivity" is unspecified in the caseof heat transfer. The classical approach to obtaining thetransport mechanism for the heat transferproblem follows the laminar approach ; namely,the momentum and thermal transport mechanismsare related by a factor, the Prandtlnumber Pr. Hence, combining the laminar and"eddy" viscosities one obtains the Boussinesq relation

$$\frac{\tau g_c}{\rho} = (\nu + \varepsilon_M)\frac{\partial U}{\partial y}$$

for the shear stress and the analogous relation

$$\frac{\dot{q}''}{\rho c_p} = -\left(\frac{\nu}{Pr} + \frac{\varepsilon_M}{Pr_t}\right)\frac{\partial T}{\partial y}$$

for the heat flux. The quantity Pr, is known as the turbulent Prandtl number.

Thus if one knows the eddy viscosity and the turbulent Prandtl number the heat transfer problem can be solved. A number of experimental and theoretical investigations have been devoted to obtaining the eddy viscosity. Only a few studies have been made of the turbulent Prandtl number. No previous experimental studies have been reported on the effect of blowing or suction on ***Pr***

Review ofprevious works

Kestin and Richardson [l] recently reviewedthe status of the turbulent Prandtl number.They found that the results from the few experimentalstudies were in conflict. The results frommercury experiments in pipes indicated that***Pr,*** >1 while gas experiments in pipes showed***Pr,*** <1. Thus it is not clear whether the turbulentprandtl number is completely independentof the molecular Prandtl number. The results ofLudwieg [2], as shown in Fig. 1, and others [l]for air flowing in a pipe do not agree.

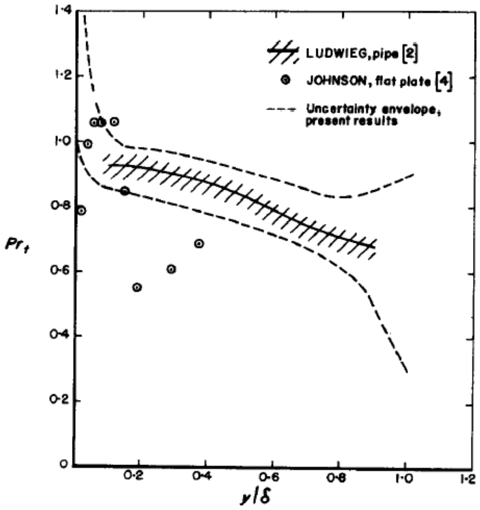

Fig. 1. Comparison of experimental results.

In a brief account of these investigations,Kestin and Richardson [l] concluded that Ludwieg'sresults are the most reliable for air flowingin a pipe. The flow at the center of a pipe doesnot include regions of intermittent wake-likeflow, such as occur in the outer region of anexternal boundary layer. On extrapolation ofLudwieg's results on the basis of the reciprocal ofdistance from the wall, they found that hismeasured values were asymptotic to a turbulentPrandtl number of 0.5 at large distances from thewall. This is in agreement with the value of 0.5deduced by Fage and Faulkner [3] from thewake of a cylinder and by Reichardt [l] in a free jet. The value of 05 is also obtained from Taylor'svorticity transport theory [3], which givesfurther support to the trend of Ludwieg's results.The only experimental study of Pr, on a flatplate with a constant free-stream velocity knownto the authors was reported by Johnson [4], whoused hot-wire anemometers to determine thedistribution of velocity and temperature fluctuationlevels. He studied the temperature distributiondownstream of an unheated starting lengthwhere the thermal boundary layer was containedat all times in an inner fraction of the momentumboundary layer, providing no information aboutthe outer region. Johnson compared the turbulentshearing stress and the heat flux obtainedby hot wire measurements with those generatedfrom mean velocity and temperature distributions,finding a 50 per cent discrepancy in theshearing stresses and good agreement for theheat fluxes. He noted that the skin-frictioncoefficients obtained by several independentmethods did not agree. The anomalous behaviour was attributed to threedimensionality of theflow. As shown on Fig 1, the scatter of the ***Pr,***data points is considerable. Even so, the averageof these results near y/S x O-1 is in fair agreementwith Ludwieg's results.As concluded by Kestin and Richardson, thequestion of the turbulent Prandtl number isunresolved and merits further experimentalinvestigation not only for air but for fluids of awide range of molecular Prandtl number.

II. OBJECTIVES OF THE PRESENT WORK

There is little consistent experimental evidenceas to the distribution of Pr, in the boundary layeron a flat plate for air. There exists no publishedexperimental study of the effect of blowing andsuction on the turbulent Prandtl number.The Pr, can be determined by measurementsof velocity and temperature distributions in theboundary layer, and the heat flux and shearstress at the wall. Such measurements have beenreported by Simpson [5] and Whitten [6] for awide range of blowing and suction conditionswith constant free-stream velocity and constantwall temperature. The blowing conditions weresuch as to hold the blowing parameter Bconstant. The experimental Stanton numberand skin-friction coefficient results associatedwith these data have been previously described[5-81]. A description has been given of the flowcharacteristics associated with these data.In broad terms, the objectives of the presentwork are to determine the turbulent Prandtlnumber Pr, for air from the data of Simpson andWhitten and to compare these results withavailable theories.

III. CONCEPT

Reynolds [l] was the first to assume thatPr, = 1 on the basis of a heuristic argumentwhich notes that in a fully turbulent field, bothmomentum and heat are transferred as a resultof eddies. From Figs. 6-8 one can see thatReynolds' argument fails to hold in detailthroughout the boundary layer. The local valueof Pr, > 1 near the wall (y' < 150) where thesmall scale turbulence is strongly affected bymolecular kinematic viscosity. The ***Pr, -c*** 1 inthe outer region (q > 005) where v has littleinfluence. Likewise, it is suspected that A affectsthe transport of heat near the wall and has littleinfluence in the outer region.6.1 ***Inner region, Pr, 2*** 1: ***background information***Jenkins [21] devised a model to account forthe unequal loss of momentum and thermalenergy from an eddy in flight between mixingpoints for a ***Pr*** + 1 fluid. For coherence themain points of this model are presented. Heargued that if the temperature of the eddy didnot change in flight, then the definition of themixing length. Treating the effects of molecular viscosity onan eddy in flight in the same manner as theeffects of molecular thermal conductivity, heobtained the following relation with experiment near the wall and fails in theouter region. This model agrees with the ideathat small scale wall turbulence is governed bymolecular properties (near wall) but fails toaccount for the large eddy motion in the outerregion. The following hypothesis accounts forthe effect of this large eddy structure. As pointed out by Hinze [14] from the workof Townsend [20], the transfer of mainstreammomentum, a vector quantity, appears to be avelocity gradient related process associated withsmall scale turbulence. On the other hand,turbulence energy, a scalar quantity, appears tobe mostly diffused by the large eddies [lS, 203,at least in the outer part of the boundary layerwhere the diffusion term in the turbulenceenergy equation is most important. This part ofthe turbulence energy diffusion has been represented. The effective velocity at which the turbulence energy is transported in the y-direction. It is not entirely surprising that the Jenkins model agrees, within experimental uncertainty,large eddies [22]. To determine the value and variation of thequantity q through a boundary layer, thefollowing approximate model is proposed. Bradshaw[18] has noted that at the outer edge of aself-similar boundary layer flow, such as the flow considered here, VP is equal to the mean rate of propagation of turbulent fluid into thefreestream-the "entrainment velocity". Although no information is available for theeffect of blowing or suction on G(q) and z/p?,it is assumed that this resulting ***VP/U,*** variation,which is roughly linear in q, applies for all casesconsidered here. It is assumed that 1 t 1, the mixing length ***1,*** andthe mean temperature gradient ***aT/ay*** arerelated. One is now in a position to calculate Pr, andhence cH from the turbulent flow structure ofthe boundary layer and the molecular *Pr.* In theinner region *Pr,* is found to be described withinexperimental uncertainty, by equation (26) whileequation (35) describes the outer region. as suggested by Rotta [12] for unblown flows.Using equation (38) the velocity "law of thewall" for the inner region, and the "velocitydefect law" for the outer region, he calculatedthe Reynolds analogy factor *St/(C,/2)* = 1.16for *Pr* = O-72. Whitten [6] obtained *St/(Cf/2)*= 1.16 from the experimental heat transfer andskin friction results associated with the presentprofiles. Equation (38) is seen to agree with thecalculated results within O-05, to be within theuncertainty envelope of the experimental results,and to produce a Reynolds analogy factor agreeing with the experimental value. Hence equation (38) should be a reliable Pr, distri-bution for 0.1 < q < 1.0 for all blown, sucked and unblown constant freestream velocity flows.

IV. CONCLUSION

The designedExperimental turbulent Prandtl number results from the velocity profiles of Simpson [5]and temperature profiles of Whitten [6] havebeen presented for constant free-stream velocityconstant ***B flows*** (-0.48 <***B*** <6.78). A description has given of the procedure used inobtaining these results.Near the wall in the region of U+ vs. y+similarity, the molecular viscosity and Prandtlnumber and the small scale turbulence governthe momentum and heat transport. Pr, > 1 andcorrelates best with the inner variables E&J andy+. In the outer region Pr, < 1 and is correlatedagainst the characteristic coordinate ~1 No effectof blowing or suction on Pr, can be seen frompresent experimental results

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