A PIONEERING ERA IN CONVECTIVE HEAT TRANSFER RESEARCH*)

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ABSTRACT

Convective heat transfer research had a pioneering era in the years between 1900 and 1930. Wilhelm Nusselt demonstrated by similarity analysis that a dimensionless parameter describing heat transfer [the Nusselt number] can be expressed as a function of Reynolds and Prandtl numbers for forced flow of a constant property fluid and as a function of Grashof and Prandtl numbers for natural convection. This created the possibility to correlate and generalize experimental results. Ernst Schmidt formulated the heat-mass transfer analogy, again for a constant property situation, which allows one to obtain relations for mass transfer processes from equations describing analogous heat transfer situations without any additional experiments.

Analysis of heat transfer could be performed after Ludwig Prandtl simplified the Navier-Stokes equations to the boundary layer equations for fluids with small viscosity and after he had formulated the mixing length theory describing turbulent transport processes.

Much of our present knowledge and understanding of heat transfer is based on these pioneering contributions.

INTRODUCTION

Convective heat transfer was late among the engineering sciences to develop into a systematic and coherent body. This is probably due to the fact that convective heat transfer is interconnected with fluid mechanics but is more involved because it requires temperature differences so that local variations of the thermodynamic and transport properties are involved. Buoyancy forces may cause natural convection currents superimposed on forced flow. It was, therefore, only at the beginning of this century that a basic understanding and the ability to calculate heat transfer evolved. Munich, the city which has been selected for this year's International Heat Transfer Conference, played an interesting role in this development. This will become evident later on in the lecture. At first we have to briefly discuss fluid mechanics which had to be developed before a basic understanding of convective heat transfer could be approached.

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SIMILARITY

In Fluid Mechanics

The fundamental laws of mechanics were known since Isaac Newton [1] and have been formulated for fluid flow in the Navier-Stokes equations [2,3]. However, solutions to these equations could only be obtained for a few simple situations and even there they often did not agree with experimental results, for instance, with those describing the pressure drop connected with fluid flow through pipes. Neither did many of the experimental results correlate among themselves.

This was changed by a study by Osborne Reynolds, the results of which he reported on the 22nd of February 1880 together with a demonstration. The apparatus which he used for this purpose is shown in a figure from his paper [4] and is reproduced here in Fig. 1. Water was contained in a horizontal trough with glass walls. A glass tube was located horizontally inside the trough. It had a bell mouth on its left hand end and was connected on its right hand to a vertical pipe. Water could thus enter the tube from the trough and its discharge could be regulated by a valve. The flow rate of water was measured by a float on the water surface in the trough and an indicator

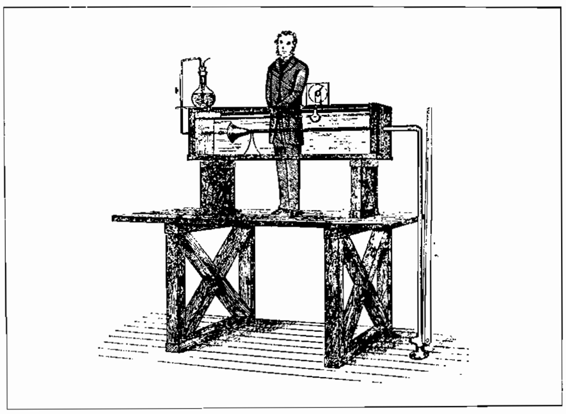

Fig. 1 Osborne Reynolds' demonstration setup

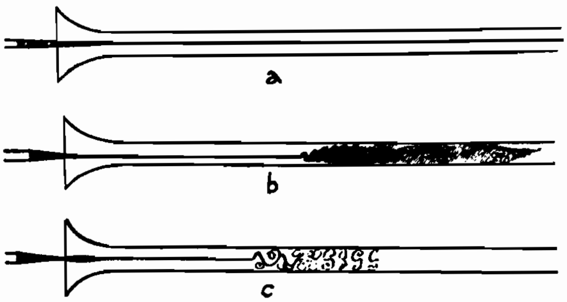

Fig. 2 Reynolds' sketches of flow observation

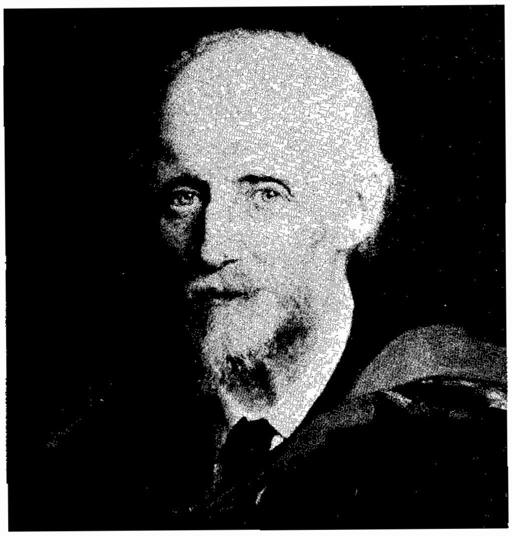

Fig.3 Portrait of Osborne Reynolds (1904)

connected to it. Reynolds explained that by normal viewing we cannot understand the details of the flow because water is transparent so that we cannot observe what happens inside it. He, therefore, introduced a small amount of colored fluid into the water at the tube entrance and observed what he called a color band as it moved through the tube after he had waited several hours before the start of the experiment to make sure that any disturbance in the water had died down. Sketches of what he observed are again taken from his paper as Fig. 2. Figure 2(a) shows that, at slow flow rate, the streak of colored water was completely straight and steady, indicating an ordered laminar flow. He observed that this persisted as the flow rate through the tube was increased until a certain value was reached where the colored streak changed its appearance quite suddenly to that

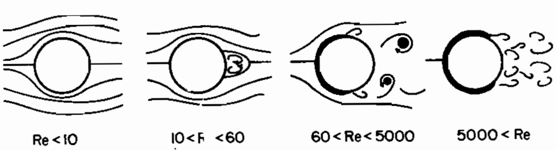

Fig. 4 Flow around a cylinder

shown in Fig. 2(b). This indicates that the color band started fluctuating and dispersing into the main flow. Reynolds also observed this flow with illumination by an electric spark. Figure 2(c) indicates that, with such an instantaneous illumination, waves and vortices are observed downstream of the location where the color band becomes unstable. Reynolds called this flow sinuous. Today we refer to it as turbulent. He repeated the experiments at different temperature levels and found that the transition occurred at lower flow rates as the temperature in the water increased.

The fact that the viscosity of water decreases with temperature may have led him to the conclusion which he reported in a paper published in 1883 in the Philosophical Transactions [4]. There he argued that the characteristics of the flow are expected to be determined by the ratio of the inertia forces to the viscous forces in the fluid and he established as the ratio of these forces the expression

$$\frac{\rho v r}{\mu} \tag{1}$$

with ρ denoting the density of the water, v the mean velocity through the tube, r the tube radius and μ the viscosity of the water. He, therefore, concluded that the transition from laminar to turbulent flow should occur at a certain critical value of this dimensionless number. In the years between 1880 and 1883, he carried out a large number of experiments with tubes of different sizes and with different liquids and established that the transition to turbulence occurred at a critical number between 1900 and 2000, when it is based according to Eq. (1) on the tube radius. He also found that a dimensionless parameter obtained by dividing the resistance R of the flow through the tube by ρv^2 is proportional to a certain power of the parameter listed under (1) according to the expression

$$\frac{R}{\rho v^2} \sim \left(\frac{\rho v r}{\mu}\right)^{n-2} \tag{2}$$

His own experiments as well as those of previous investigators correlated with the parameter $n = 1$ for laminar flow and and $n = 1.723$ for turbulent flow except for some of Darcy's experiments with an incrusted pipe which resulted in the value $n = 2$. Reynolds also realized through his studies that the value of the

Table 1

Circumstances conducive to	
Direct or steady motion:	Sinuous or unsteady motion:
1 Viscosity of fluid friction which continually destroys disturbance, (treacle is steadier than water)	5 Particular variation of velocity across the stream, as when a stream flows through still water
2 A free surface	6 Solid boundary wall
3 Converging solid boundaries	7 Diverging solid boundaries
4 Curvature with the velocity greatest on the outside	8 Curvature with the velocity greatest on the inside

critical parameter depends on the type of flow and in 1884 he published a table (see Table 1), in which he lists those factors which delay and those which advance transition to turbulence [5].

The importance of Reynold's contribution was readily recognized and he was invited to give a lecture on it at the Royal Institution as early as 1884. A reproduction of his portrait painted in 1904 and in the possession of the University of Manchester is shown as Fig. 3. The dimensionless parameter in equation (1) is referred to as Reynolds number with ample justification. Reynolds' studies provided the guideline for the correlation of experimental results in all the years up to the present and in this way advanced our understanding of fluid flow tremendously. Figure 4, as an example, presents sketches of the flow characteristics around a cylinder with circular cross section, indicating that they depend solely on Reynolds number and, therefore, are valid for any fluid, be it a liquid or a gas and for any cylinder diameter. Flow characteristics similar to those shown in Fig. 4 for flow around a sphere describe, for instance, the details of the flow around a small object like a tennis ball or a golf ball in the same way as flow around a large balloon or a storage tank for gas or liquids. Osborne Reynolds can, therefore, certainly be considered as a pioneer in the field of fluid mechanics and convective heat transfer.

In Heat Transfer

Sir Isaac Newton published a paper in 1701 in which he reported what appeared to be the first temperature measurements up to 600°C [6,7]. For the higher temperature range, he used as thermometer an iron bar which he preheated and then exposed to a constant air stream to cool it down. He observed the time at which small samples of metals or alloys placed on the iron bar solidified. He derived an equation describing the relation between the temperature of the bar and the cooling time from an energy balance of the bar and he extrapolated with its help the temperature scale which he had established with a different thermometer up to 232°C. For the energy balance he conceived what is now called Newton's law of cooling which is written today in the form

$$Q = \alpha A \theta_w \qquad (3)$$

Q denotes the heat lost by the bar per unit time into the surrounding air stream through its surface A, θ_w denotes the excess temperature of the bar [the difference between the bar temperature and the temperature of the air stream], α is called today film heat transfer coefficient. Newton was obviously aware that this coefficient depends on the specific conditions of the experiment, for instance, on the air velocity, a fact which was sometimes forgotten later-on . Equation (3) is today universally used to describe convective heat transfer in spite of objections to its practicality which are raised from time to time. It has a solid base in the fact that, according to the conservation equations, a linear relation exists between the heat flux Q and

Fig. 5 Sir Isaac Newton (1725)

the excess temperature θ_w for a fluid with constant properties. Experience has also shown that the deviations from this linear relation are small for many heat transfer situations. A portrait of Newton, who thus established the first relation for convective heat transfer, is shown in Fig. 5.

Many experimental results became available for convective heat transfer since the publication of Newton's paper but no general relations could be obtained for many years. Only in the twentieth century a breakthrough occurred at the Technische Hochschule, München, Germany.

Oscar Knoblauch who occupied a chair for Applied Physics at this institution [now Technical University Munich] since 1902 attracted many researchers to his laboratory which later on became well-known in the field of heat transfer, among them Max Jakob, Wilhelm Nusselt, Heinrich Gröber, Ernst Schmidt, Helmut Hausen, and Sigmund Erk. Wilhelm Nusselt, who studied Mechanical Engineering at this University and then became Knoblauch's assistant during the years 1907-1909, published a paper in 1909 based on his habilitation thesis in which he applied for the first time dimensional analysis to the flow and energy transport equations. This paper, together with a second one published in 1915, was pioneering in that it provided the means by which general relations could be obtained from his own experiments or from experiments published in the literature.

In the paper published in 1909 [8], he reports the results of an analytical and experimental study of heat transfer caused by turbulent flow through a tube. He assumed that the heat transfer coefficient introduced by Newton, (Eq. 3), can be expressed as a product of the influencing parameters, each raised to a characteristic power. Assuming additionally that the properties on which the heat transfer depends can be considered as constants, he derived the following equation by dimensional analysis

$$\alpha = C \frac{\lambda_w}{d} \left(\frac{\rho u d}{\mu}\right)^m \left(\frac{\mu c}{\lambda}\right)^n \qquad (4)$$

with C denoting a constant, λ the thermal conductivity, c the specific heat of the fluid, and d a characteristic length. The other parameters have been defined before. He concludes from the energy equation that the two components, m and n, should have the same value. From experiments for turbulent heat transfer in a tube which he conducted with air, CO_2, and the city gas and from experiments by M. Jakob with superheated steam he obtained the value 0.786 for m and 0.85 for n and he concluded that these values are sufficiently close to verify the conclusion m = n, and thus he derived the final relation

$$\alpha = C \frac{\lambda_w}{d} \left(\frac{\rho c v d}{\lambda} \right)^m \tag{5}$$

Today we know that his value for n is too high, and that his conclusion, m = n, is not justified. He worried about the fact that the properties in this relation vary actually with temperature and proposed as an approximation to introduce the thermal conductivity at the wall temperature, where it is indicated by the subscript w , and it, as well as the other properties, at an average temperature in the bracketed parameter.

His second paper entitled "The Basic Law of Heat Transfer" [9] and published in 1915, is the more important one. In it he applies dimensional analysis to natural convection heat transfer, dropping the restriction that the heat flux is expressed as a product of the parameters raised to some power. He still considers the properties as constant with the exception of the density, the variation of which is expressed by a thermal expansion coefficient (Boussinesq assumption), and derives the following equation for the heat flow, Q, per unit time

$$Q = \lambda d \theta_w \phi \left(\frac{\lambda}{\mu c}, \frac{d^3 \rho^2 g \gamma \theta_w}{\mu^2} \right) \tag{6}$$

The gravitational acceleration, g, and the thermal expansion coefficient γ appear in this equation in addition to the parameters defined before; d denotes a characteristic length.

This time he extends the analysis to a gas in which the properties depend in the following way on the absolute temperature, T

$$\rho = \rho_o \left(\frac{T_o}{T} \right), \quad \mu = \mu_o \left(\frac{T}{T_o} \right)^a$$

$$\lambda = \lambda_o \left(\frac{T}{T_o} \right)^b, \quad c_p = c_{po} \left(\frac{T}{T_o} \right)^c \tag{7}$$

The index, 0, refers to a characteristic fluid temperature. He derives the following result for the heat transfer coefficient, α

$$\alpha = \frac{\lambda}{d} \phi \left(\frac{d^3 \rho^2 g}{\mu^2}, \frac{\lambda}{\mu c_p}, \frac{T_w}{T_o} \right) \tag{8}$$

It took a considerable number of years before the relations derived by Nusselt were generally accepted. This may have been caused by the fact that equation (5) was based on the erroneous assumption m = n and also that heat transfer processes in engineering applications operate in general with fairly large temperature differences whereas the derivation of equations (4) and (6) hold strictly for a constant property fluid or for vanishingly small temperature difference. A book on heat transfer by A. Schack [10], the second edition of which appeared in 1940, devotes a considerable portion to an attempted proof that dimensional analysis does not work and the criticism raised in recent years against dimensionless relations under the heading "The New Heat Transfer" [11] reflects the same objection. Relations of the form as derived by Nusselt, however, have in the meantime been widely accepted and are, today, a tool used generally by those working in heat transfer. The following names have been given to the dimensionless parameters appearing in the equations

$$\text{Nusselt number } Nu = \frac{\alpha d}{\lambda}$$

$$\text{Prandtl number } Pr = \frac{\mu c_p}{\lambda} \tag{9}$$

$$\text{Grashof number } Gr = \frac{g \gamma \rho^2 d^3 \theta}{\mu^2}$$

and the expression for forced convection can thus be written as

$$Nu = f(Re, Pr) \tag{10}$$

and for natural convection

$$Nu = f(Gr, Pr) \tag{11}$$

Heat transfer information has, in many cases, to be obtained by experiments and presentation of the results in the form of equations (10) and (11) is the means to unify and generalize them.

It is my opinion that the most important step in the analysis by Nusselt was the introduction of an ideal constant property fluid. Only in this way could he get to the simple general equations (10) and (11). The equations describing heat transfer in dimensionless parameters become more involved as soon as one attempts to consider the temperature dependence of the properties. Equation (8), derived by Nusselt, actually holds only for those gases which have the same value of the exponents, a, b, and c. The equation changes to the form

$$Nu = f\left(Gr, Pr, \frac{T_w}{T_o}, a, b, c \right) \tag{12}$$

when it is used to describe generally heat transfer in gases the properties of which vary according to the relations (7). This is evidence for the fact that dimensionless relations describing heat transfer become the more restricted the more accurately

Fig. 6 Wilhelm Nusselt (~1940)

Fig. 7 Ernst Schmidt [~1942]

one tries to describe the fluid properties. The large value of relations of the form of equations (10) and (11) lies in their generality. They hold for groups of fluids with the same Prandtl number. They are exact in the limit of small temperature difference and experience has shown that they describe with fair approximation conditions at larger temperature differences when average values for the fluid properties are introduced. They are, today, found in any textbook, and Wilhelm Nusselt, therefore, can be considered as another pioneer in heat transfer (Fig. 6).

In Heat-Mass Transfer

An important relation between heat transfer and mass transfer was derived by W. K. Lewis in 1922 [12]. The mass transfer process which he investigated was evaporation of a liquid into a gas stream. He defined a mass transfer coefficient, β, by an equation analogous to equation (3)

$$W = \beta\, A(C_w - C_o) \qquad (13)$$

with W denoting the mass flux of vapor away from a liquid surface of area A, C denotes the vapor concentration (mass per unit volume of the mixture), and the indices, w and 0, indicate that the concentration should be introduced in equation (13) at the liquid surface and at a reference point in the gas stream, respectively. He established the relation

$$\beta = \frac{\alpha}{\rho c_p} \qquad (14)$$

between the mass transfer coefficient and the heat transfer coefficient, known today as Lewis relation.

The exact formulation of the heat-mass transfer anology is due to Ernst Schmidt, who studied electrical engineering at the Technische Hochschule, München, obtained his Doctor's Degree at the Laboratory for Applied Physics of the same university and was appointed professor at the Technische Hochschule, Danzig in 1925.

In 1929 E. Schmidt presented a paper entitled "Evaporation and Heat Transfer" [13] in which he investigated the restrictions under which relation (14) is valid and in which he established the relations for the heat-mass transfer analogy by a dimensional analysis of the differential equations describing conservation of mass, momentum, and energy. He considered forced convection as well as natural convection. The thermodynamic and transport properties had again to be considered as constants. The main results reported in the paper by Schmidt can be formulated as the following rule for conversion of heat transfer relations to those describing mass transfer with the following dimensional parameters

$$\text{Sherwood number } Sh = \frac{\beta L}{D} \qquad (15)$$

$$\text{Schmidt number } Sc = \frac{\nu}{D} \qquad (16)$$

The symbol D denotes the mass diffusion coefficient, L, a characteristic length:

We will assume that a relation of the form (10) is available to describe a heat transfer process in forced convection. The Nusselt number in the heat transfer relation has then simply to be replaced by the Sherwood number and the Prandtl number by the Schmidt number for an analogous mass transfer process. This procedure is indicated in the following lines

$$\underset{Sh}{\not{Nu}} = \phi(Re, \underset{Sc}{\not{Pr}}) \qquad (17)$$

The rule gives the correct relations for the limiting situation in which the differences in temperaand in concentration are vanishingly small, and it is valid for independent anologous heat and mass transfer situations as well as for a combined heat and mass transfer process. Schmidt also showed that the Lewis relation (14) follows from dimensional analysis for the condition Sc = Pr.

Two situations are treated separately in considering natural convection and the discussion is restricted to gases. In the first one, the analogy is established between a heat transfer process without mass transfer and an isothermal mass transfer process. Natural convection flow in the second process is generated by local differences in the density or the molecular weight, M, of the two components involved in mass transfer. Accordingly, a new mass transfer Grashof number is defined by the equation

$$Gr_m = \frac{gL^3}{\nu^2}\left[\frac{M_o}{M_w} - 1\right] \qquad (18)$$

The process through which the heat transfer relation can be transformed to a mass transfer relation for a analogous process is sketched in the following

$$\underset{Sh}{\not{Nu}} = \Phi(\underset{Gr_m}{\not{Gr}}, \underset{Sc}{\not{Pr}}) \qquad (19)$$

If heat transfer and mass transfer occur in the same field, then the Grashof number takes on the form

$$Gr^* = \frac{gL^3}{\nu^2}\left[\frac{M_o T_w}{M_w T_o} - 1\right] \qquad (20)$$

and the process connecting the relation describing heat transfer with the one for mass transfer is sketched in the following line

$$\underset{Sh}{\not{Nu}} = (Gr^*, \underset{Sc}{\not{Pr}}, \underset{Pr}{\not{Sc}}) \qquad (21)$$

which indicates that the Schmidt number and the Prandtl number have to be interchanged in the process.

In a paper published independently in 1930,[14] Nusselt came to the same conclusion as Schmidt. He pointed out additionally that, in the dimensional analysis, one has to consider the boundary conditions in addition to the differential equations. The boundary condition in evaporation of vapor from a liquid surface into a gas stream, however, is different from the boundary condition describing heat transfer on a solid surface insofar as a convective mass flow occurs at the evaporating liquid surface whereas such a mass flow is absent at the heat transfer surface. In the meantime, transpiration cooling has found attention in the form of a cool gas ejected through a porous wall into a hot gas stream. In this case, a convective flow occurs at the porous surface and similarity in the boundary conditions is established to the mass transfer process described above.

The analogy found initially little attention in Germany but it was readily accepted in the United States and the term Schmidt number for the dimensionless property ratio spread in the literature. In the meantime it found wide application because more information is available on heat transfer than on mass transfer. It is also used in reverse direction to obtain heat transfer relations through mass transfer experiments which, in many situations, can be carried out more conveniently and with more accuracy than heat transfer experiments. The main contribution to this analogy is, in my opinion, the pioneer paper by E. Schmidt; a photograph of him is shown in Fig. 7.

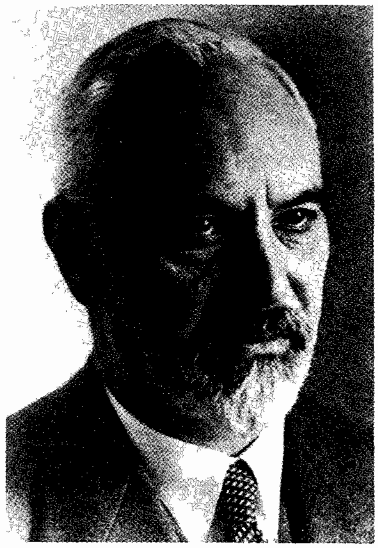

Fig. 8 Ludwig Prandtl [∿1938]

ANALYSIS

Boundary Layers and Turbulence

Dimensional analysis provides the parameters with which experimental results can be generalized and it is very useful in its way; but it does not lead to an understanding of the detailed mechanisms and interactions of flow and heat transfer processes. Only mathematical analysis combined with well-planned experimentation can accomplish this. The analytical prediction of flow and heat transfer processes had to overcome two hurdles: A way had to be found to solve the Navier-Stokes equations and a proper model had to be conceived which describes the effect of turbulence.

Important contributions to both of these tasks are due to Ludwig Prandtl (Fig. 8). He studied mechanical engineering at the Technische Hochschule, München and, after a year in industry, was appointed professor at the Technische Hochschule, Hannover in 1901. In his famous paper entitled "The Movement of Fluids with Very Small Friction" [15] and presented at the Third International Congress of Mathematicians at Heidelberg in 1904, he argues that the influence of a small viscosity of the fluid becomes noticeable only in regions with large transverse velocity gradients, primarily in those close to surfaces exposed to the flow, whereas the main body of the fluid can with good approximation be considered as frictionless. For its analysis, well developed methods were already available. The layers close to solid surfaces in which friction is important have to be thin in order to produce large transverse velocity gradients. On this basis, Prandtl simplified the Navier-Stokes equations to the differential equations describing laminar two-dimensional boundary layers. It took his student, H. Blasius, four more years to solve the boundary layer equations for steady laminar flow over a flat plate [16], but Prandtl presented a number of semi-quantitative flow fields obtained by quadrature. Among those was the one reproduced in Fig. 9 , which is found in every textbook on fluid flow. It shows the onset of separation of a boundary layer in a region where the pressure increases in flow direction.

The paper which contains just eight equations also presents a number of photos obtained in a water tunnel. It is interesting to observe that the two contributions which advanced our understanding of fluid flow enormously, namely the one by Reynolds on transition to turbulence and the one by Prandtl on boundary layers, were both obtained by flow visualization using simple equipment. Figure 10 shows the water channel with a hand-operated paddle wheel in which Prandtl made his early studies.

Many more solutions to Prandtl's boundary layer equations have been obtained in the meantime. The analysis was extended to convective heat transfer by E. Pohlhausen, who introduced, in addition to Prandtl's velocity boundary layer a thermal boundary layer within the temperature field adjacent to a heated surface. His paper [17] in 1921 treated in this way heat transfer between a solid body and a fluid with small friction and heat conduction; and in 1930, Pohlhausen solved the temperature and velocity boundary layer in free convection on a heated vertical plate based on measurements by Schmidt and Beckmann [18].

Ludwig Prandtl, who had moved to Göttingen in 1904, also provided an important impetus to the analysis of turbulent boundary layers with his mixing length hypothesis published in 1925 [19]. It served as a starting point for the development of the analysis of turbulent flow processes in the succeeding years.

Heat Transfer

A contribution to the analysis of convective heat transfer had already been provided by Osborne Reynolds in 1874 [20] in a paper in which he postu-

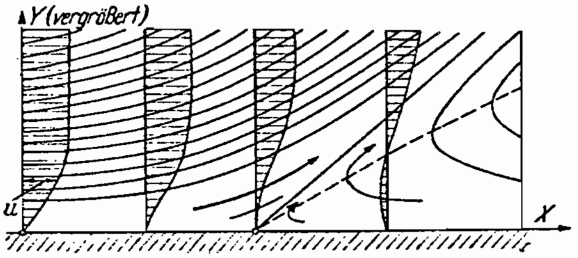

Fig. 9 Flow separation in a boundary layer

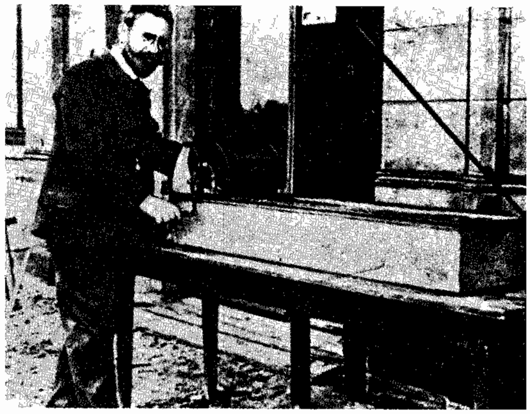

Fig. 10 Prandtl's water tunnel at the Technische Hochschule, Hannover [1904]

lated an analogy between turbulent transfer of momentum and heat. Nusselt was also suggesting in his habilitation thesis a similarity between resistance and heat transfer. Prandtl took up this idea after reading Nusselt's thesis in 1910 [21]. He recognized that Reynolds' analogy provides a satisfactory relationship between momentum and heat transfer caused by turbulent convection; but for many fluids, it is not satisfactory for an analogy between viscous momentum transport and heat transfer by conduction. To take care of this, he introduced a model with a sub-layer within the turbulent boundary layer. Prandtl's paper served as a starting point for later developments on turbulent flow and heat transfer.

CONCLUSION

The pioneering developments in the years up to 1930 started an intensive and fruitful research activity into which soon other countries joined, especially the United States of America, where the names William H. McAdams [22] and Llewellyn M. K. Boelter [23] became well-known. This activity is still strong today with research in all fields of heat transfer. It is furthered by the International Heat Transfer Conferences - the first of which was held at London in 1951 - and which are now organized every fourth year. The International Journal of Heat and Mass Transfer, started in 1958, and the International Centre of Heat and Mass Transfer organized in Yugoslavia also contributed to distribution of information on a worldwide scale.

Research activities in the last 50 years became so widespread that it is impossible to discuss the important contributions in the frame of this lecture. This growth is primarily due to the large variety of parameters which determine a heat transfer process. Table 2, in which parameters influencing a specific heat transfer process are listed, has been prepared to illustrate this. Examples of such parameters are arranged in four groups starting with the system or geometry describing a specific situation, followed by a second group listing the forces which determine fluid flow, and by a third group containing energy modes and energy transport mechanisms. The fourth group lists the fluids, the properties of which influence convective heat transfer. Any combination using a parameter in each of the groups can determine a specific heat transfer situation and many of these combinations actually occur in engineering developments. In addition, several of the parameters in the same group may become involved in, for instance, combined natural and forced convection. This raises the question of how a worker in the field can absorb, digest, and organize the overwhelming amount of information to which he is continuously exposed. I think that the pioneer contributions discussed in this paper show the way. All of them started out by simplifying the actual process, by neglecting parameters of minor impact, and by idealizing the fluids involved. Today electronic computers make it possible to describe a special heat transfer process in great detail and accuracy, but, we should not forget to cover in our research larger groups in a wide sweep and in this way to maintain a coherent and organic view of the whole field of heat transfer.

Table 2

1. System
one component: rare
two component, solid-fluid, without phase change,
  solid in bulk; tube, flat plate, cylinder, sphere
  solid dispersed:x) porous matrix, grains, fibres
  solid dispersed,x) moving: fluidized bed, dust, soot
two component,x) solid-fluid, with phase change,
  evaporation, boiling, condensation
two-component,x) fluid-fluid
more component:x) unsaturated porous media
2. Forces
  pressure
  inertia
  gravity
  centrifugal, Coriolis
  electric, magnetic
  surface tension
  molecular
3. Energy Mode and Energy Transport

kinetic	conduction
chemical	convection
internal	diffusion
	diffusion-thermo

4. Fluids
  Newtonian—liquids, gases,
  Non-Newtonian
  plasma

x) considered as continua or particulates

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