COMMUNICATION—THE INSTRUMENT OF SCIENTIFIC DEVELOPMENT

TWENTY YEARS "INTERNATIONAL CENTRE FOR HEAT AND MASS TRANSFER"

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In Herceg Novi, a famous and much-loved resort on the Dalmation coast, the constitutional meeting of the "International Centre for Heat and Mass transfer" took place in September 1968. The motivation of the founders was to establish a centre which would encourage international cooperation and the exchange of ideas and theories in the field of heat and mass transfer through the organisation of conferences, seminars and workshops, and by the publication of reports and scientific papers. As we have heard, the centre has successfully achieved these aims and will undoubtedly continue to fulfil the vision which lies behind them.

In the late sixties other independent developments occured which helped the emancipation of the field of heat and mass transfer: the foundation of the "Assembly for International Heat Transfer Conferences" which would be responsible for organising an international conference every fourth year; and the foundation of the "Internationlal Journal for Heat and Mass Transfer," which was seen as the represemtative mouthpiece of the worldwide community. These undertakings were also accompanied by national activities—the foundation of new journals and new teams—which were now able to offer their theories and results on an international level.

The exchange of scientific information is a condition for development, but its foundation is the achievement of the individual researcher, who recognizes the discoveries of his predecessors, develops them, and passes them on to his successors. So, every successful scientist is a link in a long chain of conversation which stretches over generations up to our time—and which is our responsibility to continue. This process of "taking and giving" can be illustrated by some outstanding examples in our field, and this, the 20th anniversary of our centre, seems an appropriate occasion to reflect upon this process and its importance for us all. The scientists of our generation are successors of their elder colleagues and will, hopefully, become the predecessors for the younger generation.

The first example I should like to consider concerns scientific thermometry at the turn of the 18th century, i.e., in the period before exact natural science. Later examples concerning the exchange of heat and mass in turbulent flow both involve two of my predecessors at the Technische Universität München, Wilhelm Nusselt, and Ernst Schmidt.

THERMOMETRY

The beginnings of the measurements of temperature remain in historical darkness. Our first certain knowledge is that around 1650 quite adequate liquid thermometers (wine-spirit-in-glass) were being made in Florence by a group of italian scientists who were pupils of Galileo [1]. These "Florentine thermometers" stimulated further development, especially in Paris at the Académie des Sciences (Guillaume Amontons, 1702), and in London at the Royal Society (Isaac Newton, 1701) . Florentine thermometers were also later produced by other thermometer makers inside and outside Italy, and were often sold by travelling salesmen. In this process, they underwent many modifications: they became more beautiful and solid on the outside, but their readings ceased to be congruent. However, people remained content as long as the meniscus did not diasappear in the sphere on cold days and hot weather did not cause the capillary to explode. The distance between extreme readings was divided into degrees whose number and value varied at whim. Nobody could claim adequate calibration and there were frequent complaints of the absence of "corresponding weatherglasses."

It was, however, using a thermometer of the Florentine style that Daniel Gabriel Fahrenheit [2] from Danzig discovered (or rediscovered) that the only possible method to produce corresponding thermometers in series is to calibrate the scale between two reproducible fixed points. It was in 1706 or 1707 (when he was 20 or 21 years old) that he thus put the Florentine scale back on a solid basis. At this point the form of the scale remained unchanged viz.: a central zero-point (approx. 10°C), with scale extending in both directions to 90–100 degrees.

In 1708, whilst in Copenhagen, he met the Danish astronomer Olav Roemer and absorbed from him the idea of a scale extending in tone direction from a low zero-point. Roemer himself had set his ice-point at 7.5 degrees. Fahrenheit thought this value awkward and altered it to 8 degrees; he also felt that Roemer's degrees were too large and subdivided them into four for his own scale. Thus the ice-point on this (his second) scale was labelled $4 \times 8 = 32$, a value which he always retained and which is still the basis of today's Fahrenheit scale.

After preliminary experiments in Berlin in 1713, and following his move to Amsterdam, Fahrenheit introduced his third scale for quicksilver thermometers, which he produced in series from 1717 onwards. The use of quicksilver as a medium was inspired by Amontons, who had observed that a quicksilver column was noticeably longer in summer than in winter (at the same air pressure). Fahrenheit was also inspired by Amontons' observations of boiling phenomena to carry out investigations in this direction and for this, of course, wine-spirit as a medium was impossible.

The linear extrapolation of his wine-spirit scale gives a steam-point of approximately 205°F whilst Fahrenheit himself gives a value 212°F—identical to our modern value. The reason for this variance lies in his move from Berlin to Amsterdam, since whilst he had earlier used Potsdam glass for his capillaries, in Hollandd he utilized Amersfoort glass. Although it was as a consequence of this that he first became aware of the impact of glass types on calibration, he chose to retain the value of 212 as the boiling point—probably in order not to confuse his erstwhile customers. It is worth stating, however, that without his move to Amsterdam water would boil today at 205°F instead of 212°F!

Once Fahrenheit had finally found how to measure temperatures in a exact, reproducible, and comparable manner he was also then able to measure thermodynamic properties such as density, boiling temperature, and the expansion coefficient.

He went on to discover the subcooling of water in the freezing process, the dependence of the boiling temperature on pressure, and to establish the first steam tables. The

Royal Society honoured his efforts in 1724 by making him a Fellow. As a result of this, his thermometers and their scale received rapid acceptance in England and, later, in the United States and in the British Empire, where, even today, despite the onset of metrification, Fahrengeit's scale is still in wide use.

As a younger British colleague remarked to me: "Even more than a decade after metrification, here in my laboratory it may be 20°C, but at home it is definitely 68°F.

TURBULENT HEAT EXCHANGE

The oldest model for the exchange of heat between a solid wall and a moving fluid seems to date from Isaac Newton (1701) [3]. Newton imagined that particles of the fluid stream pass the wall in steady flow, absorbing heat during their period of contact. This view contains elements of what we know today as "penetration theory." Newton concluded from his model that the heat taken up is proportional to the temperature difference between wall and fluid. Thus Newton was able to define his "law of cooling" as follows: "So equal parts of air are heated for equal times and take up heat which is proportional to the heat (here temperature) of the iron." (sic enim aeris partes aequales aequalibus temporibus calefactae sunt et calorem conceperunt calori ferri proportionalem) [3].

It was the influence of velocity on heat exchange that Osborne Reynolds (1874) [4] chose to examine. He was inspired by the observation that the blast-pipe in a locomotive boiler adjusts the production of steam pretty much to the work required. ("It has been a matter of surprise how completely the steam-producing power of a boiler appears to rise with the strength of blast or the work required from it.") According to some specialists, it was the introduction of the blast-pipe by George Stephenson which made the steam locomotive a useful machine.

Reynolds imagined that the turbulent main flow in a tube produces a continuous crossflow towards and away from the wall which transports each property of a volume element. Thus this crossflow (later called "Reynolds flow") caused flow resistance by transferring the momentum of the mainflow towards the wall, these appearing as shear stress. However, this crossflow also transfers the enthalpy of the mainflow to the wall, where it is then experienced as heat flux.

It seemed reasonable to Reynolds to consider heat exchange proportional to the product of density and velocity; and also flow resistence proportional to the product of density and velocity squared. He thereby also expressed that the exponent of the velocity of flow resistence must be greater by the power one than that of the velocity of heat exchange.

Here we have the first formulation of the analogy between flow resistence and heat transfer, later to be called the "Reynolds Analogy", which was to be the starting point for many future developments. Although we know today that this analogy holds true only under certain conditions, for rough calculations involving gases it can, nonetheless, still be applied even in its original form. We will mention here that the proportion of the crossflow (Reynolds flow) to the main flow is generally a small percentage.

It was a very long time before further consequences were drawn from this work of Reynolds, particularly since it was published only in a very obscure journal (Proceedings of the Literary and Philosophical Society of Manchester). Wilhelm Nusselt [5] complained even in 1909 that for practical calculations the heat transfer of gases and liquids were treated alike, despite Reynolds' previous emphasis on the importance of the mass flow. A critical collection of contemporary works by Richard Mollier (1897) [6] suggests how little progress had been made since Reynolds—at least on the subject of forced convection. In this work of 1909 (his habilitation thesis for theTechnische Hochschule Dresden) Nusselt analysed the differential equations for the momentum exchange and heat exchange with respect to the influence of the major parameters velocity, density, viscosity, and heat capacity. His experimental results had shown that the influence of each parameter could be approximately represented by power products. The dimensional analysis done by Nusselt showed the mutual dependence of the exponents. Each of these values was confiremed by the experiment, and Nusselt was able to describe flow resistance and heat exchange in a tube solely by dimensionless parameters. Nusselt published an extension of this work to include free convection in 1915. These two works are milestones on the way to fuller understanding of heat exchange. Nusselt's achievement can be seen most clearly by comparing Heinrich Gröber's collection of experimental results published in 1912 [8] with the work of Mollier (1897) mentioned above and indeed it seems justifiable to divide the development of heat transfer into pre-Nusselt and post-Nusselt eras.

An important side result of Nusselt's work in 1910 was the experimental finding that the exponent of the the velocity for heat exchange ($m = 0.786$) is smaller than the exponent for the pressure drop ($n = 1.776$) by a figure closely approaching one. Nusselt commented. "This would strongly suggest that the relation $n - m = 1$ holds true for the two exponents, at least in the case of smooth tubes." This hypothesis stimulated Ludwing Prandtl to investigate the analogy between pressure drop and heat transfer for tubes under more general conditions. In his work of 1910 [9] (written "in the countryside") he divides the tube flow into a laminar sublayer adjacent to the wall (with pure shear stress and pure heat conduction) and a turbulent core flow. At the boundary, the momentum flow and the heat flow must be equal. Thus Prandtl succeeded in projecting flow resitance against heat exchange with particular reference to a new dimensionless parameter, which was later to be named the "Prandtl number" in his honour. This is, in fact an extension of Reynolds' work (1874) of which Prandtl apparently had no knowledge. Prandtl's equation was recognized independently shortly after by G. J. Taylor (1916/17) [10].

In a later work (1928) Prandtl completed his earlier observations by using more experimental results and the consequent equation is known today as the "Prandtl analogy." It was the beginning of a pejoiod of rapid development which continued right up into the 70's and is described at length in current textbooks [12].

TURBULENT MASS EXCHANGE

The development of our understanding of mass exchange in turbulent flow is considerably more recent than that of heat exchange, although the processes of development have much in common. Wilhelm Nusselt (1916) [13] seems to have been the first to consider the combustion of coal as a mass transfer of oxygen from the air to the surface of the coal, introducing a "combustion number" which was calculated from the analogy of the heat transfer coefficient.

W. K. Lewis (1922) [14] concerned himself with the evaporation of liquid into gas. The liquid (water, toluol, chlorbenzol) evaporated from a wick which was placed in a stream of gas (air or carbon dioxide). The evaporation enthalpy necessary for this had to be replaced through heat transfer. From these experiments, he confirmed his theory and derived a single relationship between the coefficients of heat and mass transfer; this was later to be known as the "Lewis relation."

Ernst Schmidt (1929) [15] researched the same process in a more mathematical form. His base was the complete set of differential equations of heat and mass transfer and he found that the Lewis relation holds exactly true only in the special case where the thermal diffusivity and the diffusion coefficient are equal. He also observed the process of free convection using, for example, a clay plate saturated with water, suspended in the air. The interest these issues attracted in the 20's and 30's is indicated by papers published by Nusselt (1930) [16] and A. P. Colburn (1930) [17]. It was Colburn (1933) [18] who suggested that the quotient of properties used by Schmidt shoud be called the "Schmidt number". The quotient of Schmidt number and Prandtl number is today known as the Lewis number.

CONCLUDING REMARKS

All three examples show the interaction of communication and individual scientific achievement. Every scientist plays a dual role in this process, receiving, and handing on. Communication is the instrument in this process, a necessary but not sufficient condition. One might, therefore, conclude that without communication scientific development is not possible. This understanding is the moral and technical justification to utilize and improve all possible channels of communication.

Our centre has been at the forefront of the development of the processes of communication during the last twenty years. Its material and intellectual investments have born rich fruit. On this occasion of its jubilee, we wish it and its staff every further success for the future.

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