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ALLAN PHILIP COLBURN—THE YEARS WITH DU PONT

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IT WAS a fortunate circumstance that brought Allan Colburn to the Du Pont Experimental Station, 23 September 1929. A research group in chemical engineering had just been organized, under the far-sighted administration of C. M. A. Stine, Chemical Director, and A. P. Tanberg, Director of the Experimental Station, paralleling and extending the groups set up to undertake fundamental research, not tied to immediate commercial objectives, in polymer chemistry, headed by W. H. Carothers, in colloid chemistry, and in catalysis.

The chemical engineering group, which I had the privilege of heading, was built around the nucleus of men who had been working on improvements in the manufacture of acids, but Colburn was one of the very first additions made to prosecute the fundamental research objectives. He had conducted at the University of Wisconsin, with O. A. Hougen, a noteworthy investigation in the field of heat transfer [19]. It was this, indeed, which brought him to the attention of the Du Pont Company, and it was natural, therefore, that heat transfer was the topic assigned to him for study.

The objectives of the research group in chemical engineering were to find out what was known about the several unit operations, with the aim of making information available to the people engaged in the design of plants that would lead to the specification of equipment and methods of operation that would be the most economical and give the greatest assurance of satisfactory performance. Colburn fell in readily with these objectives. He attacked his assignments with unfeigned zeal, and found, I feel sure, real satisfaction in carrying them out.

The chemical engineering research group, with a unified central aim but with the members each responsible for separate topics, provided a congenial atmosphere, refreshed and stimulated by the frequent visits of W. H. McAdams as a consultant.

Colburn's first publication from the Experimental Station was in a sense an extension of his Wisconsin thesis [6]. His work there was directed towards improving the design of dehumidifying gas coolers used in the manufacture of city gas. It is cited here as establishing the early date of his putting forward of the "Colburn analogy", as it might better be called, even though not in the exact form in which it has come to be known.

In this paper Colburn extended the idea he first developed in the second part of his earlier publication [18]; namely, that the incorporation of the ratio of the molecular diffusivity to the momentum diffusivity (kinematic viscosity) should accomplish for mass transfer in conduits what the Prandtl and Taylor modifications of the Reynolds analogy did for heat transfer, with the function of the Prandtl number called for to conform to the velocity distribution in turbulent flow. Colburn was able to show that the corresponding expression did show agreement with the Wisconsin data on dehumidification, as well as with data obtained some years before at the Experimental Station by C. H. Greenewalt on the drying of air with sulfuric acid in a falling film column.

The group of three papers published in 1931 exemplifies Colburn's special talents [2, 7, 20]. The chemical engineering group was, among other things, looking into the possibility of designing an integral converter–heat exchanger for the catalytic conversion of SO_2 to SO_3, and Colburn undertook to carry out tests to determine the heat-transfer coefficients we could expect in a tube packed with catalyst pellets, and the resulting pressure drop. The experiments, carried out at the Repauno Works, where facilities were more readily available than at the Experimental Station, did provide the necessary information (though the converter was never built, at least not by us). But it was Colburn's special genius that he was not satisfied with the application to the immediate problem at hand, but that he was impelled to generalize upon the data collected and formulate a method of attack upon the next problem or series of problems.

The first paper in the series [7] reports the enhancement of heat-transfer coefficients (six- to tenfold) when a tube is packed with granules, the enhancement being a function of the ratio of the particle to the tube diameter. The second [2] reports the pressure drop data, and goes on to propose a method of correlation of the data, together with earlier data of F. C. Blake, G. B. Taylor, and F. C. Zeisberg, and other data from the literature. The correlation, based on two simple propositions, proved remarkably successful. The two underlying ideas were that the dimension of the void spaces should, to a first approximation, be proportional to the dimensions of the packing particles; and that although much of the pressure loss was due to expansion and contraction, the effect of velocity on these losses might be the same as for skin friction, both in the turbulent and the viscous regimes. Finally [20], as a result of a visit to Schenectady, Colburn was able to include in drawing conclusions about the relationship of the enhancement of heat transfer to the increase of pressure drop an extensive set of measurements carried out at General Electric on a variety of "turbulence promoters". These were found not to vary as much with design as might be expected, with regard to effectiveness, measured in terms of the increase they gave in heat transfer for the same increase in pressure drop. The increase in heat-transfer coefficient was always found to be less than would be obtained by merely increasing the velocity in the empty tube to that which would cause the same pressure drop. Increases up to about sixfold in heat transfer could be obtained without increase in superficial gas velocity, but at the expense of increase up to about 200 times in pressure drop.

In 1932, Colburn interested himself in spreading the gospel of heat transfer by responding (outside his duties at the Experimental Station) to an invitation from the editor of Food Industries to contribute a paper on "What heat-transfer theory tells in the food plant" [8]. For example, he was able to show in simple fashion that experimental data on sterilization of tomatoes in cans could be predicted quite accurately by the usual unsteady-state conduction equations, assuming only that the contents had all the properties of water, except mobility, a fairly reasonable assumption at that.

In the same year, although not published until 1933 [5], Colburn joined with other members of the group in giving the profession, through the American Society of Mechanical Engineers, the benefit of several charts we had prepared to facilitate design calculations, since then reprinted in a succession of texts and handbooks. The charts incorporated the principle of line-coordinate charts, making it possible to include the physical property data on many common substances right on the chart representing the equation of correlation.

In the same vein, always with the aim of bringing theory into the service of the design engineer, Colburn published [10] a clever mathematical derivation to simplify the calculation of heat exchangers where the coefficient can be expected to vary along the length of the exchanger. If it can be assumed to vary linearly with temperature, he showed that the heat-transfer rate would be correctly given by the logarithmic mean of $U_1\Delta t_2$ and $U_2\Delta t_1$, the subscripts indicating terminal values.

I have no way of knowing which of Colburn's publications he considered the most significant; I never thought to ask him. I believe he might have been inclined to agree with my appraisal of the paper he gave at the Chicago Meeting of the American Institute of Chemical Engineers in 1933 as the most important: "A method of correlating forced convection heat-transfer data and a comparison with fluid friction" [9]. That is was considered important by the profession is attested by the fact that it won for him, in 1935, the first impression of the Wm. H. Walker Award of the A.I.Ch.E. "for an outstanding contribution to the chemical engineering literature" published in its *Transactions* during the three previous years.

It is an important paper. It is one of the most penetrating and most inclusive studies of heat-transfer data published. In it Colburn employed the "Colburn analogy" for heat transfer, in the form in which it has become familiar, using simply the 2/3 power of the Prandtl number as the correlating factor, admitting that was purely empirical, but seeing that it was practically indistinguishable in its effect from the Prandtl–Taylor function over a range of Prandtl numbers from about 1 to 50, and had the merit of simplicity and convenience for calculation on the slide rule. The resulting "*j*-factor" method of analysis gave a rational basis for interpreting numerous puzzling sets of data at Reynolds numbers just above and below the transition from viscous to turbulent flow.

I well remember the sense of excitement that Allan brought with him when he came over to my house one evening to show me the first of the plots presented in this paper, showing how the data in this region gave the same appearance as the well-known "dip" in the friction-factor curve.

There is, of course, more in the paper. I think it worth while to reproduce it in its entirety.

This is the place to bring out a point not apparent from the title of the paper or even from the abstract. Reading of the legend for Fig. 16, however, makes it plain that it was here that Colburn presented, almost as an afterthought, the "Colburn analogy for mass transfer" in the form in which that has become established, with the 2/3 power of the Schmidt group.

A sort of footnote to this paper appears [12] as discussion of a paper by Kaye and Furnas; it presents the interpretation of some further sets of data by the *j*-factor method.

Resuming the chronological account of Colburn's publications, we come upon one [11] in which he extends Nusselt's formulation for the conductance of a layer of condensate on the wall of a condenser tube to include the transition to turbulent flow. The resulting design equations, agreeing with experimental data from the literature, indicate an increase, rather than a further decrease, in the heat-transfer coefficient when the condensate rate (per unit of periphery) increases past the critical value of the Reynolds number.

In a 1934 paper Dr. Colburn extended some work presented by his mentor, Professor Hougen, a little earlier, and with the help of some others in the chemical engineering research group, gave a detailed example of the reliable method for the calculation of cooler condensers for mixtures of vapors with noncondensing gases [19]. It consists in determining local values of $1/U\Delta t$ at a sufficient number of points along the path of gas flow to permit calculation of a correct average by graphical integration. The local values are obtained, through trial and error, by equating the heat transferred through the condensate, the tube wall, and the cooling-water film, to the sum of the heat transferred by the sensible cooling of the gas and the latent heat equivalent of the vapor transferred by diffusion and condensed. The analogy equation facilitates the estimation of this last quantity. The necessary surface area is then obtained by multiplying the heat transferred per hour by the integrated value of $1/U\Delta t$.

There have been several attempts to shorten the labor involved in the trial-and-error solution, all at some loss of accuracy. Naturally, the greatest saving in labor is now obtained by programming the computations for an electronic computer.

At the same 1934 symposium of the Division of Industrial and Engineering Chemistry of the American Chemical Society, I presented on behalf of Dr. Colburn the paper [3] which is most often cited as the source of what is frequently referred to as "the Chilton–Colburn analogy". As mentioned earlier, the idea dates back to Colburn's paper of 1930, and is set out unequivocally, if inconspicuously, in his paper of 1933. In any event, it might be called the Colburn–Chilton analogy, if it were not that Ch comes before Co in an index, and we were committed to a policy of listing authors' names alphabetically, without any implication of seniority or degree of contribution to the work reported. Several sets of data, in addition to those cited in the 1930 paper [6], were shown to give support to the modified Reynolds analogy equation, for situations where the flow of the fluid is parallel to the heat transfer surface. For other situations, there is still good correspondence between the *j*-factors for heat transfer, incorporating the 2/3 power of the Prandtl number, with those for mass transfer, with the same function of the Schmidt group.

Later the same year, at the first "Christmas Symposium" of the I. & E.C. Division, I presented, again on behalf of Dr. Colburn, the paper [4] in which we set forth the H.T.U. concept ("height of a transfer unit"). We had actually been making use of this concept for some time, at first loosely calling it by the same name as an earlier worker at the Experimental Station, W. A. Peters, Jr., had given to his factor for representing the effectiveness of a packed column, the H.E.T.P. ("height equivalent to a theoretical plate"). While for many cases, in distillation particularly, the numerical values of the two may be nearly the same, this is not so for absorption, generally—only if the operating line and the equilibrium line are parallel, in fact. It is the H.T.U. that is theoretically applicable to a differential process, as in a packed or spray tower. It has, moreover, the advantage over the mass-transfer coefficient (to which it can be directly related) of having, like the H.E.T.P., a single dimension, length; and it turns out, like the *j*-factor (to which it is also related), not to vary widely with flow rate.

The H.T.U. concept has now entered into the language, so that it is hardly necessary to recall that it was proposed to designate by the expression N.T.U. ("number of transfer units") the result of integrating the differential change in vapor concentration divided by the instantaneous driving force. The H.T.U. is then merely the height of the packing divided by the N.T.U.

Interesting himself more and more in mass transfer and its applications, including distillation, Colburn obtained by a process of simplification and mathematical analysis at which he was particularly adept, a convenient formulation for the effect of entrainment on plate efficiency [13]. The result can be briefly stated. The apparent efficiency, E_a, is related to the contacting efficiency, E_v, the weight fraction of entrainment, e, and the reflux ratio, R ($= L/V$) by the expression: $E_a = E_v/(1 + eE_v/R)$. Colburn goes on to conclude that some entrainment can be tolerated, and that the limit on column capacity may not be entrainment but loading, the physical limit for countercurrent flow of vapor and liquid

Attacking a basic problem in heat and mass transfer, Colburn and T. B. Drew published in 1937 a paper [15] dealing in fundamental fashion with the condensation of mixed vapors. They showed that the composition of the condensate depends on the rate of condensation, varying from the equilibrium value to the same as the vapor stream as the rate increases.

The reader will have noted in the foregoing the implication that Allan Colburn was not always available to present some of these papers in person. Indeed, for a considerable portion of his period with Du Pont he suffered a succession of encounters with tuberculosis. Such a seemingly short time ago, this was before the advent of modern therapeutic measures, and it was only by his own indomitable courage, the care of his devoted wife, and heroic treatments at the hands of his physicians and surgeons, that he was returned to a state of reasonably good health. In such a state, it seemed, when a request came from the University of Delaware for someone to join their Department of Chemical Engineering, that it would be advantageous for Allan to have a situation where he might be able to fix his own schedule rather than to feel it necessary to keep up the pace in an industrial laboratory. Accordingly, the invitation was put before him, and he left the Du Pont Company in April 1938 to accept it. This was a great loss for the chemical engineering research group, mitigated in part by his retention as a consultant.

Much of Colburn's work had related to improvements in processes carried out or under design in the Du Pont Company, and did not result in publications, except as he was able to extract generalizations from it. Some work remained that was later prepared for publication, and it is now in order to review these papers briefly.

The first of these [14] deals with an extension of the H.T.U. concept to cases where the resistance of both the gas and liquid "films" are important. The relation of the over-all H.T.U. to the separate film values is simply:

$$H_{OG} = H_G + (mG_m/L_m)H_L$$

This is a more manageable relation than that connecting $K_{G}a$ with $k_{G}a$ and $k_{L}a$, since the H values vary only moderately with gas and liquor rates, and (mG_m/L_m) is limited, in practical cases, to a narrow range. Hopefully, a plot of H_{OG} vs (mG_m/L_m) for experimental data would give a straight line, with H_G as the intercept and H_L as the slope. Several sets of data appeared to yield to this treatment, though it must now be admitted that the procedure has not proved as useful as hoped for, doubtless on account of the large number of variables that affect measured values of the H.T.U.

In a piece of work carried out experimentally by A. G. Edison, Colburn dealt with the formation of fog in the condensation of vapors in the presence of non-condensable gas [17]. Fog is produced if the temperature tends, on the removal of heat, to cross the saturation curve. It was shown that it could be prevented if a small amount of sensible heat is added to the mixture along the length of the condenser.

A widely quoted paper [1] represents a study carried out with the collaboration of H. C. Carlson. In it, it was shown that vapor–liquid equilibrium data are capable of ready evaluation and extension if calculated in terms of activity coefficients, or deviations from Raoult's Law. These factors are related one to another by the Gibbs–Duhem equation, and the integrated forms of this equation, such as Van Laar's, permit the calculation of complete equilibrium curves from azeotropic compositions, total pressure or boiling-point curves, or liquid–liquid solubility.

An experimental investigation carried out in the early 1930's was reported belatedly at a symposium on high pressures [16]. It was intended to determine if there was an effect of high pressure as such on heat-transfer coefficients. Experimental measurements using synthesis gas (75% H_2, 25% N_2) at pressures from 30 to 900 atm gave values in conformity with data on gases at ordinary pressures, after making the required (small) allowance for changes in the physical properties.

CONCLUSION

Personally, to his associates, Allan Colburn was the most companionable of men, always amiable, eager to help, and tolerant of the views of others. Professionally, with such a record of publications as here reviewed, I think there can be no disagreement with the conclusion that he is entitled to a place among the foremost of those who have made notable advances in the theory and practice of heat and mass transfer.

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