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ALLAN PHILIP COLBURN—THE YEARS IN EDUCATION

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ALLAN COLBURN'S early professional career has been outlined by his good friend and co-worker, Thomas Chilton, in a companion paper in this publication. The two men collaborated directly in a number of important pieces of work which contributed magnificently to the new field of chemical engineering, in its adolescent stages in the United States at the time. Theirs was a unique opportunity to apply scientific tools to the many new and intriguing problems of chemical manufacture afforded by the growth of an important chemical company. Through them, and a few others with similar insight, chemical engineering became known to practicing engineers and to students alike as a professional field unique among the engineering branches in its opportunities to use the basic sciences, including chemistry, and mathematics for a wide spectrum of problems characteristic of the chemical and petroleum industries.

Thus, it was with a well-known reputation for original work having practical significance that Allan Colburn came to the University of Delaware in 1938 to head a fledgling department in what was then a small and unimpressive college. Some have said that he made the change so that he would be free to follow a less physically demanding schedule. Those who knew his work in these early days remember his almost boundless energy and his devotion to his new responsibilities, not only in his own department but in many other affairs at his institution. Allan Colburn's father had been a school teacher; it appeared to Allan's friends that he, too, had found his place in the world. Even his plan to take a nap after lunch each day for the sake of his recovery from illness was soon discarded in favor of the many new interests which he found on the campus.

Naturally, there was much work that was incomplete at the time of the transition from industry to teaching. The important papers [10, 12] on the transfer-unit concept and its use in treating experimental data as well as engineering design were yet to appear, but the thoughts behind them quite clearly came from the industrial years. A new interest in thermodynamic properties of solutions, frequently pointed out by Colburn as the key problem for the whole field of distillation, had led to a series of studies of vapor-liquid compositions in collaboration with H. C. Carlson of the Du Pont Company. Today their paper [6] is one of the most widely quoted works in the field, for it set the stage for a long series of papers by chemical engineers throughout the world, a series which is far from completion.

Professor Colburn's interest in heat-transfer problems appeared again soon in his university work. Shortly after taking up his new duties he became involved as a consultant in several important investigations supporting the war effort. One of these involved the need to provide better air cooling of finned cylinders for aircraft engines. The problem was to obtain nearly uniform cooling around the circumference of the cylinder, the air flow being confined to narrow passages between the fins. The similarity to and differences from heat transfer in exchangers with parallel passages were pointed out in a publication with Lemmon and Nottage [37] in 1945.

A related paper, published by the National Advisory Committee for Aeronautics [23] was concerned with the influence of vapor bubble formation on a hot surface, above the boiling point of a liquid which flows over the surface to cool it. The vapor bubbles cannot grow except in the very thin layer of superheated liquid at the surface itself, yet their appearance in this layer, which accounts for the major resistance to heat conduction, can greatly increase the cooling rate —a problem of obvious importance for the design of liquid-cooled engine cylinders.

At about the same time the first of a series of papers on heat transfer in condensers began to appear. These undoubtedly have their origin in Professor Colburn's own doctoral thesis, done at the University of Wisconsin under Professor Olaf Hougen, but the work at the University of Delaware was directed more toward the explanation of the heat-transfer coefficients than toward discussing methods of computation in condenser design. A paper with Millar and Westwater [25] had considered the transfer of heat to condensate layers in the sub-cooling portion of a condenser. A paper written with Carpenter, Schoenborn, and Wurster in 1946 [8] was concerned with the heat transfer and fluid friction effects in the thin annulus surrounding an experimental condenser tube. Covering both laminar and turbulent flow conditions, these authors showed how to apply the heat transfer–friction analogy and how to modify it for the viscous region. For these conditions it had not been clear whether the hydraulic equivalent diameter, D_e, used to correlate the friction factors would also work for the heat-transfer problem, recognizing that friction effects occurred on both walls of the annulus and heat transfer was through one wall only. The authors concluded that D_e, defined for friction, ought to be used in the Nusselt number for heat transfer, which was found to be a function of the Graetz number involving only the mass-rate of flow rather than the linear velocity. Heat-transfer studies on the same apparatus were subsequently published with Carpenter [7] in a paper which explored, perhaps for the first time in a realistic way, the considerable influence of vapor velocity on rates of condensation inside vertical tubes. An earlier paper by Colburn [9] had shown how the onset of turbulent motion in the gravity flow of the condensate layer could improve heat transfer through it. The new work showed, however, that a turbulent vapor stream, adjacent to the falling liquid film, could produce turbulence in the film Reynolds numbers as small as 240. Under these conditions the condensation coefficient was sometimes ten times the previously expected values. The new results could be explained by assuming that the thermal resistance of the liquid layer was really that of a laminar sub-layer having the same thickness that such a layer would have in a tube filled with liquid, provided the wall shear stress was the same in both cases. Thus, the key to the problem lay in the well known universal velocity distribution function. These results and a review of other recent work [21] on condensation were presented by Professor Colburn as the James Clayton Lecture at an international meeting on heat transfer in London in 1951.

Beginning in 1949, the first of a series of papers on heat-transfer coefficients on the shell side of tubular heat exchangers appeared. It was characteristic of Colburn's interests in heat transfer that the important practical problems were given first place and this investigation, which extended over nearly fifteen years until Colburn's death, was a good example of this interest. The work was supervised jointly by Colburn and his faculty colleague, Olaf Bergelin, but the progress on the project was reviewed periodically by a Special Advisory Committee of the Heat Transfer Division of the American Society of Mechanical Engineers, composed of engineers with a working knowledge of the real problems involved and a keen interest in the usefulness of the results. In the first paper [39] data were presented from tests of an idealized heat exchanger tube bundle involving flow of an oil directly across and perpendicular to the tubes. Reynolds numbers from about 3 to 500 were achieved, both friction and heat-transfer factors being measured. Variations in tube diameter and spacing were explored in a number of subsequent studies, culminating in Engineering Experiment Station Bulletins published by the University of Delaware in 1950 [4]. Highest coefficients were obtained, for a given power loss, with small, closely packed tubes in staggered arrangements. The Colburn *j*-factor method of correlation proved to be best when the influence of the temperature gradient through the fluid was expressed with a function of the fluid viscosity.

More recently, the same series of publications continued with the appearance in 1954 of a paper with Bergelin and Brown [2] on the heat transfer and frictional effects in a baffled shell-and-tube exchanger specially designed to eliminate leakage of the shell fluid through the annuli between baffle plates and the inside wall of the shell and between the tubes and the corresponding holes through the baffles. Although such an exchanger is too highly idealized for practical use, its use in the program was a necessary step in the development of methods for treating the shell-side phenomena quantitatively. The new measurements included values of heat transfer and friction factors for the tubes occupying the baffle window regions, where the shell fluid reverses its direction. The results are summarized in a second *Engineering Experiment Station Bulletin* [5]. Finally, in another *Bulletin* [1], published after Professor Colburn's death, but reflecting a considerable influence from his earlier participation, data were published from work on still another shell-and-tube exchanger in which various leakage paths could be opened one at a time. The final result of the work was a proposed method of separating the heat transfer and fluid friction phenomena into component parts, bearing in mind the subdivision of the total shell-side stream and the recombination of the different streams at points along the heat-transfer surface.

Professor Colburn's work on the classification of vapor–liquid equilibrium thermodynamic phenomena, begun earlier at Du Pont and resulting in the now famous paper of Carlson and Colburn [6], also continued at the University. First, on the experimental side, two papers written with his faculty colleague, E. M. Schoenborn, and their students [28, 29] described laboratory equilibrium stills useful for miscible and immiscible liquid mixtures. The first still was designed to avoid the problems associated with imperfect mixing of the liquid condensate which was returned continuously to the boiler in a previously popular apparatus, by continuously recirculating a vapor stream through the equilibrium chamber until it reached a constant composition. The same idea has been adopted by several other investigators more recently.

On the theoretical side Professor Colburn became interested in the properties of ternary and multicomponent, thermodynamically non-ideal mixtures as a result of his work for the U.S. Office of Rubber Reserve during the war. The nation needed a domestic source of synthetic rubber to replace the natural product from abroad and asked the chemical industry to develop processes for producing butadiene–styrene polymer. A key step in the process involved the separation of unsaturated butene from saturated butane. This separation, difficult because of the very small difference in boiling points of the compounds, was made possible by adding a third substance of low volatility to the liquid, causing it to form non-ideal mixtures in which the relative volatility of the two hydrocarbons would be considerably enhanced. The first paper resulting from this work [38] reported data on mixtures of the hydrocarbons, one at a time, with furfural. This was soon followed by data on the ternary system *n*-butane-cis-2-butene-furfural [33, 48] resulting from work done jointly with Colburn's faculty colleague, J. A. Gerster, and their students. Finally, the work was extended to four components, including water, in a paper written with Jordan, Gerster, and Wohl [36]. For a number of years these data were among the few sets in the chemical engineering literature in which multicomponent non-ideal interactions among the components in the liquid had been reliably observed under the conditions important for extractive distillation. Professor Colburn's interest in the field was genuine. Through this interest he influenced many students and faculty friends whose work continues to appear in our literature.

Professor Colburn's friends at the University recall that he sometimes mentioned that among his different research interests his work in the field of distillation seemed to him to be his best accomplishment. This is born out by his contributions to thermodynamics of solutions and by several publications, both experimental and theoretical in character, which relate to the performance and the design of distillation process equipment. In a sense these are a continuation of the studies of mass transfer begun at Du Pont, yet they are also directed more specifically at the special characteristics of distillation equipment rather than to mass transfer in general.

The first paper [13] in this series is entitled "The Calculation of Minimum Reflux Ratio in the Distillation of Multicomponent Mixtures". It made available for the first time a short method suitable for distillation column design for fixing the minimum quantity of liquid reflux to be fed to the top of a continuous fractionating column which handles solutions of three or more compounds. Mathematically, the problem had been known for some time, yet it was a mark of Colburn's genius that he, possibly before anyone else, recognized its essential parts and indicated a logical way to solve it approximately. To some degree his procedure has now been superseded by other methods suitable only for high-speed computers and by the elegant analytical method of Underwood [47]. Colburn's method was designed for use by the design engineer who wants a quick answer and who likes a method into which he can put his own engineering judgement as he proceeds. There is evidence that, even today in spite of other developments, Colburn's method is still used. It is remarkably simple and appealingly related to the real conditions occurring inside columns.

Another analytical study of fractionating columns showed how mass balances could be applied to the unsteady state changes in the compositions of liquid held inside the column during batch-wise removal of the more volatile component. Others more recently have also shown how the inertia of the column may, under certain conditions, make the efficiency of separation of the components of a binary mixture greater than if the hold-up of liquid in the column were zero. However, Colburn and Stearns were apparently the first to point it out [30].

A series of experimental investigations involved studies of azeotropic distillation [26, 29], in which the essential problem depends on taking advantage of certain non-ideal solution behavior among the components. The work on extractive distillation of saturated and unsaturated hydrocarbons with furfural culminated in a paper [34] reporting some of the first data available on the efficiencies of bubble-cap plates. Owing to the increase in liquid viscosity brought about by the addition of a high percentage of furfural, it had been expected that the efficiencies in this important process might be very low. It was encouraging to find that they were on the order of 50 to 60 per cent and, while smaller than comparable values encountered in distillation of binary mixtures, were not so low as to make the whole operation unattractive.

The paper on extractive distillation had been preceded by another [32] in which the relationship between plate efficiency and the diffusional resistances of the vapor and liquid phases had been brought out. It seems not unlikely that Professor Colburn's influence on more recent investigations into distillation behavior was considerable, including the cooperative project carried out in three universities under the sponsorship of the American Institute of Chemical Engineers, which acted on behalf of a large group of American chemical and petroleum companies. Indeed, the correlations of data resulting from the cooperative project bear a close relationship to the ideas originally put forward by Professor Colburn.

His interest in the general dissemination of information about mass-transfer processes is shown by Colburn's contributions to engineering handbooks [14, 27, 40] and several papers of a general nature designed to make the general engineering public aware of advances in the field [15, 20, 24]. Other miscellaneous papers reporting experimental results of work with students and colleagues should also be mentioned [31, 42, 44, 45], as well as a paper concerned with economic factors in engineering design [42].

We come finally to the part of Professor Colburn's work at the University of Delaware in which he may have had the deepest interest of all and which his close friends and associates remember most vividly. This was his concern for education itself.

During the war years he had prepared the curriculum on chemical engineering for the U.S. Army, in cooperation with Professor B. F. Dodge of Yale University. Some of his ideas were set forth in a short paper contributed as a piece for a series on "Careers in Chemistry and Chemical Engineering" published by the American Chemical Society [17]. In addition, he contributed papers to professional educational societies on the teaching of the unit operation of gas absorption [11], on his organization of his graduate course on distillation [16], about graduate programs suitable for engineers who are employed in industry [19], and about the challenges of engineering as a field [18, 22]. The first of these contained much new information on the economically optimum design of gas absorbers which has subsequently appeared in textbooks [46] and handbooks [41].

The recitation of these references does not do justice to the influence of a great teacher. Professor Colburn has left us a great tradition in engineering and applied science. He, more than most teachers of his day, was able to show students through his own enthusiasm for engineering, through his quick, incisive thought, through his modesty, and through his uncanny ability to put aside the irrelevant to get to the important core of problems, that chemical engineering is an exciting field of work and study. Many engineers who occupy positions of responsibility today speak of the great influence which Dr. Colburn had on them, not only through his classroom teaching, but also through his remarkable influence upon anyone who had an opportunity to work alongside him on an engineering problem.

But this influence of the man was not only because of his rare technical ability. It was also because of his concern for people in all fields. He was active in developing the University's Institute of Inter-American Study and Research and its Institute for Human Relations, and he contributed much to the postwar growth of the University in many other ways. He was Director of the Delaware Chapter of the Red Cross and a member of the Research Committee of the Delaware Branch, American Cancer Society. His friends trusted and admired him for his understanding heart, his quick sympathy, his gentleness, his humility and his complete unselfishness.

In February, 1955, Allan Colburn died. Many honors came to him during his life and posthumously but his greatest honor is one that cannot be recorded on parchment. It is the remarkable result of an unselfish life devoted to the service of others.

REFERENCES

1. K. J. Bell, Cooperative research program on shell-and-tube heat exchangers, *Engineering Experiment Station Bulletion* No. 5. University of Delaware, Newark, Delaware (1963).
2. O. P. Bergelin, G. A. Brown and A. P. Colburn, Heat transfer and fluid friction during flow across banks of tubes—V. A study of a cylindrical baffled exchanger without internal leakage. *Trans. Amer. Soc. Mech. Engrs* **76**, 841–850 (1954).
3. O. P. Bergelin and A. P. Colburn, Miscellaneous overall coefficients of heat transfer, in *Chemical Engineers' Handbook* (J. H. Perry, Ed.), pp. 480–482, 3rd Edit. McGraw-Hill, New York (1950).
4. O. P. Bergelin, A. P. Colburn and H. L. Hull, Heat transfer and pressure drop during viscous flow across unbaffled tube banks, *Engineering Experiment Station Bulletin* No. 2. Univ. of Delaware, Newark, Delaware (1950).
5. O. P. Bergelin, M. D. Leighton, W. L. Lafferty Jr. and R. L. Pigford, Heat transfer and pressure drop during viscous and turbulent flow across baffled and unbaffled tube banks. *Engineering Experiment Station Bulletin* No. 4. Univ. of Delaware, Newark, Delaware (1958).
6. H. C. Carlson and A. P. Colburn, Vapor–liquid equilibria of nonideal solutions utilization of theoretical methods to extend data, *Industr. Engng Chem.* **34**, 581–589 (1942).
7. F. G. Carpenter and A. P. Colburn, The effect of vapor velocity on condensation inside tubes, *General Discussion on Heat Transmission*, pp. 20–26. Inst. Mech. Engrs (London) and Amer. Soc. Mech. Engrs (1951).
8. F. G. Carpenter, A. P. Colburn, E. M. Schoenborn and A. Wurster, Heat transfer and friction of water in an annular space, *Trans. Amer. Inst. Chem. Engrs* **42**, 165–187 (1946).
9. A. P. Colburn, Calculation of condensation with a portion of condensate layer in turbulent motion, *Industr. Engng Chem.* **26**, 432–434 (1934).
10. A. P. Colburn, The simplified calculation of diffusional process. General consideration of two-film resistances. *Trans. Amer. Inst. Chem. Engrs* **35**, 211–236, 587–591 (1939).
11. A. P. Colburn, Absorption of gases by liquids. *Collected Papers on the Teaching of Chemical Engineering*. Amer. Inst. Chem. Engrs, New York (1940).
12. A. P. Colburn, Simplified calculation of diffusional processes, *Industr. Engng Chem.* **33**, 459–466 (1941).
13. A. P. Colburn, The calculation of minimum reflux ratio in the distillation of multicomponent mixtures, *Trans. Amer. Inst. Chem, Engrs* **37**, 805–825 (1941).
14. A. P. Colburn, Other methods of comminution and production and application of metal powders, *Chemical Engineers' Handbook* (J. H. Perry, Ed.), 2nd ed., pp. 1982–1983; 2003–2007. McGraw-Hill, New York (1941).
15. A. P. Colburn, Heat transfer by natural and forced convection. *Engineering Bulletin, Research Series* No. 84, Purdue University, Lafayette, Indiana (1942).
16. A. P. Colburn, A graduate course in distillation, *Trans. Chem. Eng. Div. Amer. Soc. Engng Ed.*, Bucknell University, Lewisburg, Pa. (1947).
17. A. P. Colburn, Training the undergraduate chemical engineer, *Chem. Engng News*, **28**, 2513–2515 (1950).
18. A. P. Colburn, New frontiers for the engineering approach, *Chem. Engng Prog.*, **44**, 18–20 (1948).
19. A. P. Colburn, The graduate program at Delaware as related to industrial employees in cooperative education at the graduate level. Paper presented at meeting of Div. the Graduate Studies. Amer. Soc. Eng. Education (1950).

20. A. P. Colburn, Azeotropic and extractive distillation, *Canad. Chem. Process Industr.* (1950).
21. A. P. Colburn, Problems in design and research on condensers for vapor mixtures (The James Clayton Lecture). *Proc. Inst. Mech. Engrs, Lond.* **164**, 448–458 (1951).
22. A. P. Colburn, A challenge to engineering education. *Proceedings*, annual convention of Assoc. Land Grant Colleges and Universities, pp. 183–185 (1952).
23. A. P. Colburn, C. Gazley Jr, E. M. Schoenborn and C. S. Sutton, Effect of local boiling and air entrainment on temperatures of liquid-cooled cylinders. Nat. Adv. Comm. Aeron. Tech. Note No. 1498 (1948).
24. A. P. Colburn, J. A. Gerster and C. Pyle, Some recent developments in fractional distillation. *Proc. Fourth World Power Congress*. Sect. 3B. Carlo Colombo, Rome (1955).
25. A. P. Colburn, L. L. Millar and J. W. Westwater, Condenser–subcooler performance and design. *Trans. Amer. Inst. Chem. Engrs* **38**, 447–468 (1942).
26. A. P. Colburn and J. C. Phillips, Experimental study of azeotropic distillation—use of trichloroethylene in dehydration of ethanol, *Trans. Amer. Inst. Chem. Engrs* **40**, 33–58, (1944).
27. A. P. Colburn and R. L. Pigford, Sections on general theory of diffusional operations (pp. 524–559) and gas absorption (pp. 668–711). *Chemical Engineers' Handbook* (J. H. Perry, Ed.). McGraw-Hill, New York (1950).
28. A. P. Colburn, E. M. Schoenborn and D. Schilling, Equilibrium still for partially miscible liquids. *Industr. Engng Chem.* **35**, 1251–1254 (1943).
29. A. P. Colburn and E. M. Schoenborn, The selection of separating agents for azeotropic and extractive distillation and for liquid-liquid extraction. *Trans. Amer. Inst. Chem. Engrs* **41**, 421–43 (1945).
30. A. P. Colburn and R. F. Stearns, The effect of column hold-up on batch distillation. *Trans. Amer. Inst. Chem. Engrs* **37**, 291–308. (1941); Discussion *ibid.*, **37**, 727–732 (1941).
31. A. P. Colburn and D. G. Welsh, Experimental study of individual transfer resistance in countercurrent liquid–liquid extraction. *Trans. Amer. Inst. Chem. Engrs* **38**, 179–201 (1942).
32. J. A. Gerster, A. P. Colburn, W. E. Bonnet and T. W. Carmody, Plate efficiencies related to separate vapor and liquid resistances, *Chem. Engng Prog.* **45**, 716–724 (1949).
33. J. A. Gerster, T. S. Mertes and A. P. Colburn, Ternary systems *n*-butane-1 butene–furfural and isobutane-1–butene–furfural vapor–liquid equilibrium data. *Industr. Engng Chem.* **39**, 797–804 (1947).
34. E. W. Grohse, R. F. McCartney, H. J. Hauer, J. A. Gerster and A. P. Colburn, Plate efficiencies in separate of C_4 hydrocarbons by extractive distillation with furfural, *Chem. Engng Prog.* **45**, 725–737 (1949).
35. C. A. Jones, E. M. Schoenborn and A. P. Colburn, Equilibrium still for miscible liquids. Data on ethylene dichloride–toluene and ethanol–water *Industr. Engng Chem.* **35**, 666–672 (1943).
36. D. Jordan, J. A. Gerster, A. P. Colburn and K. Wohl, Vapor–liquid equilibrium of C_4 hydrocarbon–furfural–water mixtures, *Chem. Engng Prog.* **46**, 601–613 (1950).
37. A. Lemmon Jr., A. P. Colburn and H. B. Nottage, Heat transfer from a baffled-finned cylinder to air. *Trans. Amer. Soc. Mech. Engrs* **67**, 601–612 (1945).
38. T. S. Mertes and A. P. Colburn, Binary mixtures of *n*-butane, isobutane, and 1-butene with furfural. Vapor–liquid equilibria and thermodynamic properties, *Industr. Engng Chem.* **39**, 787–796 (1947).
39. G. A. Omohundro, O. P. Bergelin and A. P. Colburn, Heat transfer and fluid friction during viscous flow across banks of tubes, *Trans. Amer. Soc. Mech. Engrs* **71**, 27–34 (1949).
40. R. L. Pigford and A. P. Colburn, Plate efficiencies for distillation columns and packed distillation columns, in *Chemical Engineers' Handbook* (J. H. Perry, Ed.), 4th ed., pp. 610–621. McGraw-Hill, New York (1950).
41. R. L. Pigford and R. E. Emmert, Section of gas absorption. in *Chemical Engineers' Handbook* (J. H. Perry, Ed.), 4th ed. McGraw-Hill, New York (1963).
42. Cyrus Pyle, A. P. Colburn and H. R. Duffey, Factors controlling efficiency and capacity of sieve-plate extraction powers, *Industr. Engng Chem.* **42**, 1042–1047 (1950).
43. B. R. Sarchet and A. P. Colburn, Economic pipe size in the transportation of viscous and non-viscous fluids, *Industr. Engng Chem.* **32**, 1249–1252 (1940).
44. E. M. Schoenborn and A. P. Colburn, Rotameter calibration, *Chem. Met. Engng* **46**, 414–415 (1939).
45. E. M. Schoenborn and A. P. Colburn, The flow mechanism and performance of the rotameter, *Trans. Amer. Inst. Chem. Engrs* **35**, 359–389 (1939).
46. T. K. Sherwood and R. L. Pigford, *Absorption and Extraction*, pp. 451–544. McGraw-Hill, New York (1951).
47. A. J. V. Underwood, Fractional distillation of multi-component mixtures—calculations of minimum reflux ratio, *Inst. Petrol.* **32**, 614 (1946).
48. F. Welty, J. A. Gerster and A. P. Colburn, Vapor–liquid relation in the system *n*-butane–cis-2-butene–furfural–water. *Industr. Engng Chem.* **43**, 162–172 (1951).