Laboratory Demonstration

TEMPERATURE APPROACH IN COUNTER-FLOW HEAT EXCHANGERS

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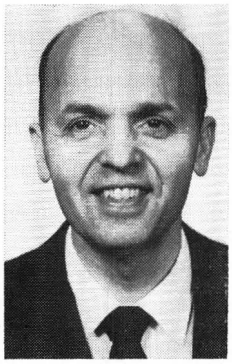

W. Henry Tucker received his B.S. in Ch.E. degree from The University of Virginia, 1942, and the degrees of S.M. and Sc.D. from M.I.T. After industrial experience with Servel, Inc., he taught at Purdue University for 16 years. In 1969 he became Chairman of Chemical Engineering at Tri-State University. He has research inteersts in heat and mass transfer with particular emphasis on absorption refrigeration. He has served as Advisor to Cheng Kung University, Taiwan, and in 1969 was awarded the first Winston Churchill Traveling Fellowship to Great Britain. In 1959 he spent a sabbatical at the Swiss Federal Institute of Technology.

SOMEWHERE ALONG the road which leads to the making of a B.S. chemical engineer who is able to understand heat transfer rate processes, we should teach him an understanding of the "pinch-point" in countercurrent heat exchangers (the point along the length of the exchanger where the temperatures of the two streams approach each other). Sometimes it is at the hot end, sometimes at the cold, and frequently, somewhere inside when there is a change of phase giving a change in the stream heat capacity. Reference 1 discusses temperature approach in a process for producing pipeline gas from coal where energy is a major cost item. The classical textbook, *Industrial Stoichiometry,* Lewis, Radasch, and Lewis, [2] thought the subject important enough to devote all of chapter 3 to it. New books tend to teach energy balances to the sophomore without relation to the heat exchanger, and transport processes follow in the junior year without reference to the equilibrium case.

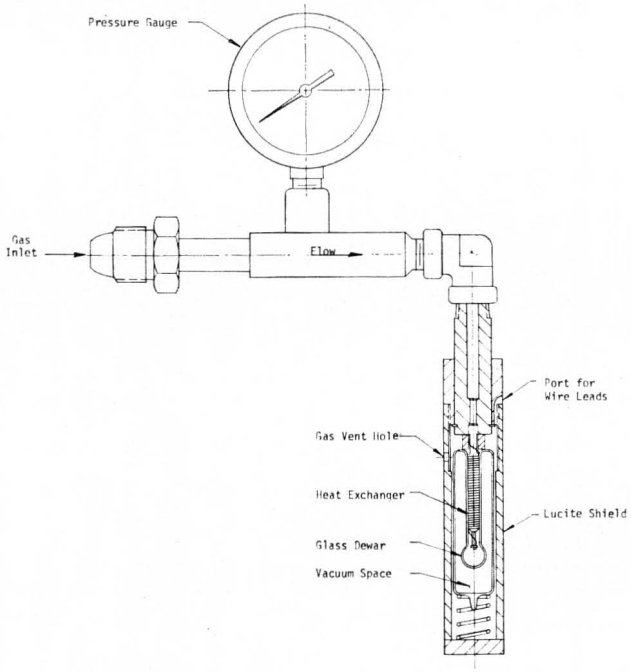

FIGURE 1. Break-away of JT Refrigeration Demonstrator.

It was the purchase of a Joule-Thomson Refrigeration Demonstrator from Air Products and Chemicals, Inc. [3] that gave the author the feeling that here would be a classical way of demonstrating this pinch-point phenomenon and how it could shift from one end of the heat exchanger to the other. This device is shown in Fig. 1. High pressure nitrogen from a cylinder (at say, 200 atm pressure), flows through the inside of a heat exchanger and expands into a glass dewar at a pressure approaching atmospheric. This is the usual way of producing a small percentage of liquid from the incoming gas stream. But this particular device has no separate exit for product

TABLE I
Temperature—Specific Enthalpy Data from Fig. 2

TEMP. °K	h (IATM) cal/mol	h (200 ATM) cal/mol
320	3046	2850
260	2630	2320
200	2210	1700
140	1790	890
77	1310 sat'd vapor	390
77	0 sat'd liq.	130

SAT'D LIQUID SPECIFIC ENTHALPY DATA

Perry's, 4 ed. p. 3-180
115K - 534 cal/mol
100 - 326
80 - 39

liquid nitrogen, so that the entire stream flows back across the heat exchanger to the exhaust port. It turns out that, instead of the usual 5% or so of liquid product, the bulb in the dewar is practically 100% liquid, which, of course, re-evaporates in its passage back through the heat exchanger.

Since the standard J-T expansion is well documented in thermodynamics, no separate experiment is needed for it here. What this article will do is to compare the heat exchanger temperature profile for the standard J-T with liquid product

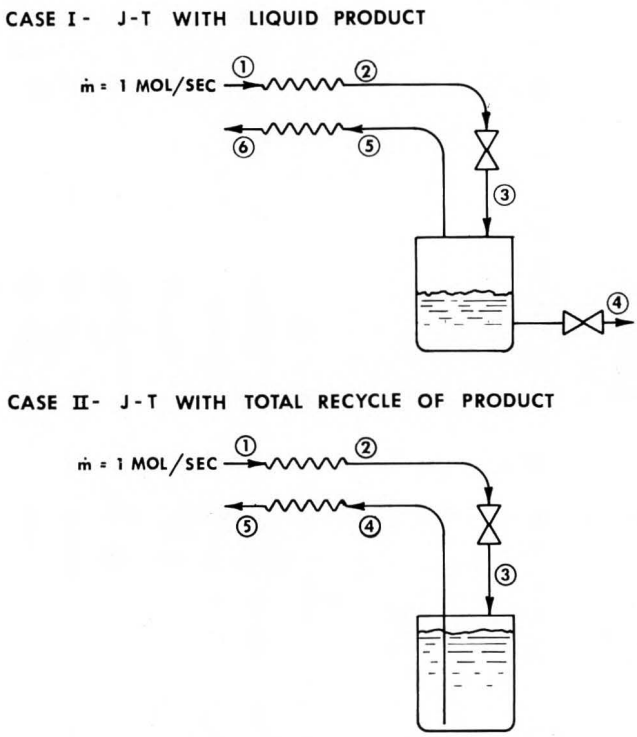

FIGURE 2. Diagrams of the two cases being compared.

(Case I) and that of the demonstrator in Fig. 1 (Case II) to show how the pinch-point shifts. See Fig. 2 for the process diagrams.

In order to obtain a temperature profile in a heat exchanger, one needs heat capacity data. Fig. 3 gives temperature vs. specific enthalpy data for nitrogen, and data for the two pressures selected, 1 atm and 200 atm, are plotted in Fig. 4, and the data are tabluated in Table I. The 1 atm data show a change of phase from gas to liquid at 77K, while the 200 atm data being above the critical pressure show no such discontinuity.

For Case I, we consider the J-T expansion giving a liquid product. To determine the percent of the feed that is liquified, one customarily wraps an energy balance around the whole system, cutting streams 1, 4, and 6 in Fig. 2. The calculations

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in Table II indicate that 8.25% of the feed would be liquified, assuming temperature equilibrium between streams 1 and 6—or the assumption of an infinite area heat exchanger. Assuming instead a 25F pinch at the warm end, the product drops to a mere 2.2% of the feed stream.

The student usually accepts this calculation without thinking the matter through. It, of course, turns out to be correct. But the basic assumption involved should be checked—that the thermal equilibrium, or "pinch" in the finite area case, occurs at the warm end of the exchanger. This is true because the heat capacity of the high pressure stream is in general greater than that of the low pressure stream. What is important is the total heat capacity of the streams. The heat capacity of the low pressure stream is even lower when the product withdrawal causes the exit gas stream to have a lower mass flow rate than that of the high pressure stream.

Fig. 5 shows the temperature profiles for the cases of zero and 25K temperature differences at the warm end. It is a plot not of specific enthalpy but of total stream enthalpy, still keeping the high pressure stream on a 1 mol/sec. basis. The low pressure stream is based first on a 0.9175 mol/sec.

TABLE II
Energy Balances for Case I, Fig. 2

0°△t – INFINITE AREA HEAT EXCHANGER

h_6 = 2915 cal/mol; t = 300K
h_4 = 0 77K
h_1 = 2675 300K

h_1 x 1 mol/sec. = $h_4(x) + h_6(1-x)$

x = *.0825 mol liq/mol feed.*

25°△t

h_4 = 0 T = 77K
h_6 = 2740 275K
h_1 = 2675 300K

h_1 x 1 mol/sec. = $h_4(x) + h_6(1-x)$

x = *0.0225 mol liq/mol feed.*

35°△t

h_4 = 0 T = 77K H_1 x 1 = $h_4x + h_6(1-x)$
h_1 = 2675 300K
h_6 = 2675 265K *x = 0, no product*

TOTAL STREAM ENTHALPY—1 ATM STREAM

T	h	H 0.9175 mol/sec.	H 0.9775 mol/sec.
320	3046	2790	2970
260	2630	2410	2570
200	2210	2025	2155
140	1790	1640	1750
77	1310	1200	1280

basis for the zero temperature difference and then on a 0.978 mol/sec. basis for the 25K difference, in accordance with the calculations on Table II. As these curves are not positioned properly at the warm end in relation to the 300K assumed feed temperature, one bodily moves the curves over to the dotted line positions—quite a small correction but this is just fortitious. Usually the displacement is greater. The reason the two curves can be moved horizontally with respect to each other is that in a heat exchanger which is assumed to be well insulated, the △H change in each stream is equal, so that only relative enthalpies are important. Temperatures at the cold end of the heat exchanger for the infinite area and for the finite area are determined by dashed lines A and B, fixed by the enthalpy of the saturated vapor leaving the separator at 77K.

One can continue the calculations on Table II for the case of a 35K temperature difference. At this selected condition, the product rate turns out to be zero, indicating the extreme importance in this process of having a very efficient heat exchanger. (This is the story of the cryogenic industry).

Now we can employ the demonstrator shown in Fig. 1 which by design allows no liquid product. We can conclude from the third calculation on Table I that we will now have a 35K △t regardless of how large the heat exchanger is (in Fig. 2, Case II, $H_1 = H_5$). This is an interesting twist, since the warm end △t can no longer respond to the area of the heat exchanger. One might inquire how this can be. By now, it might be obvious that if the temperatures are fixed at the warm end of the exchanger, the pinch temperature difference, which depends on the amount of area, must lie either inside the exchanger or at the cold end. The solution can be clearly seen on Fig. 4. This plot of specific enthalpy versus temperature is also the total enthalpy if each of the two streams is assumed to have a flow rate of 1 mol/sec. (no product withdrawal). The 35K △t is shown at the warm end. If one proceeds to the cold end, one spots a zero △t at about 93% liquid. Actually, when one runs the demonstrator, the product in the dewar collector seems closer to 100% liquid. Since the data on Fig. 3 at the 200 atm pressure are subject to considerable error at the low temperature end, the demonstrator can give a check of this accuracy even if its area is not infinite. When heat exchangers are not infinite, then the

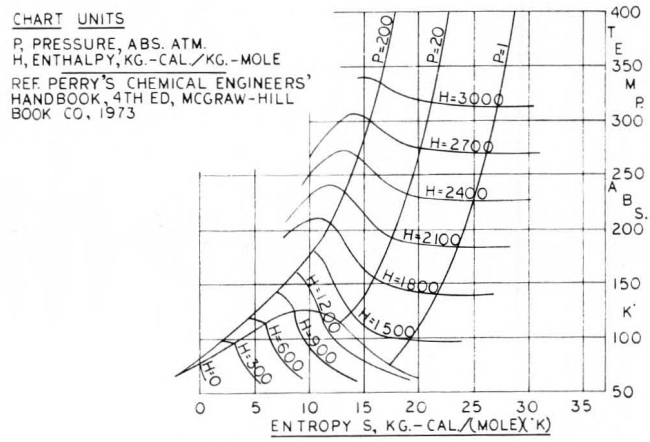
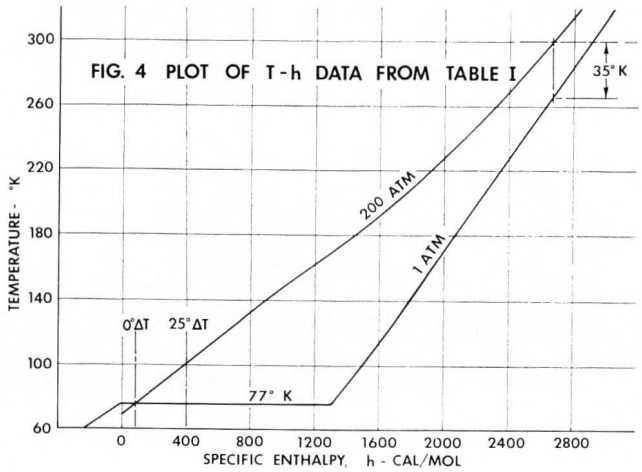


FIG.-3 THERMODYNAMIC CHART FOR NITROGEN



cold end temperatures move to the right on Fig. 4, with the 25K case being shown. Interestingly, if the area is further decreased to give more than a 35K difference, then the minimum Δt switches back to the warm end.

The curves on Fig. 4 also should indicate to the student that to size such a heat exchanger, one must break it up into the evaporating portion and the heating portion to allow the use of log-mean temperature differences, since the stream heat capacity abruptly changes. Actually, one must also estimate the film coefficients, as these are different in the two sections, and constant film coefficients, as well as heat capacities, are assumed when the log-mean relationship is derived. With no phase change, but with non-linear cooling curves (variable heat capacity), one should size a heat exchanger by point-to-point integration rather than the use of a log-mean driving force.

CONCLUSIONS

THE GRADUATING chemical engineer should go out on the job with a clear understanding of the thermal equilibrium case in heat exchangers (for infinite areas), for elegant heat transfer theory and correlations are useless if the basic equilibrium case is not even understood.

The use of the J-T Demonstrator is considered a classical way of showing the floating nature of the pinch-point, which shows up in many heat exchangers encountered on the job, when changes of phase or flow rates are encountered. □

ACKNOWLEDGEMENT

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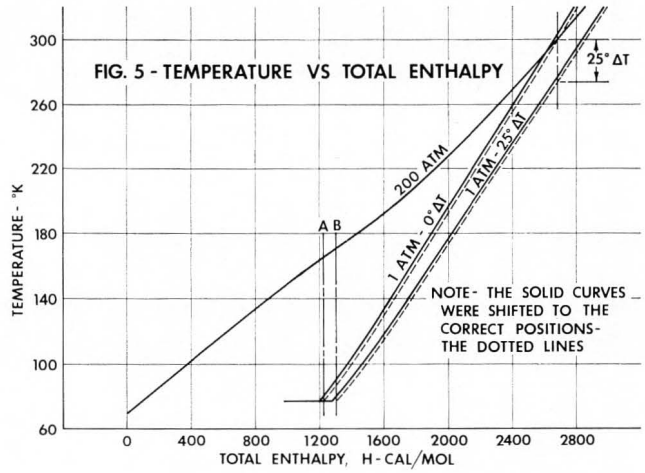

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Continued from page 32.

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