THE TEACHING OF PROCESS DESIGN

EDITOR'S NOTE: The following paper, authored by the late T. K. Sherwood in 1959 while he was a faculty member at M.I.T., was sent to CEE *by W. H. (Bill) Manogue, a member of the AIChE Education and Accreditation Committee. He credits E. L. Mongan, Principal Division Consultant in Du Pont's Engineering Service Division, for bringing it to his attention.*

Professor Emeritus J. Edward Vivian of M.I.T. has written Dr. Manogue that he and Professor Wei (Head, Department of Chemical Engineering at M.I.T.) have reviewed the manuscript and "while he agreed with me that Sherwood's conclusion is not current, he felt that as long as the publication appeared with an Editor's note that this was a historical paper written in 1959, he had no objection to publication of the complete original manuscript."

We are pleased to be able to share this historical document with our readers, with the comments above.

T. K. SHERWOOD (Deceased)
Former professor at
Massachusetts Institute of Technology
Cambridge, MA 02139

IT IS SUGGESTED that engineering design can be taught effectively by introducing design problems into various theoretical subjects. A sample thermo problem is presented in detail as the best means of explaining just how this approach can be used in a course such as engineering thermodynamics.

If this technique is to be more generally employed at M.I.T. it is necessary that a large fraction of the engineering faculty be as interested and competent in the design aspects of engineering as they are in the scientific or analytical. The fraction so inclined is perhaps already too small and appears to be decreasing.

INTRODUCTION

The typical engineering accomplishment of importance results from a sequence of (a) recognition of a social need or economic opportunity, (b) a conception of a plan as to how the need may be met or the opportunity seized, (c) an analysis of the merits of the conception and of the consequences of proceeding with the plan, (d) the building or construction of the machine, plant or bridge as conceived, and (e) its operation. Item (c) is a sort of go no-go step; if the analysis is discouraging, the conception step and the analysis are repeated.

"Engineering science" is a phrase which has come into use in recent years to describe the *analysis* step. Good engineers today must be exceedingly proficient in analyzing a concept; quantitative mathematical analysis based on first principles is one of the good engineer's most powerful tools. But it no more constitutes *engineering* than any one of the other four activities listed. In particular, it must be noted that conception ("design") comes before analysis; the analyst must have something to analyze.

As technology develops, it seems likely that those engineers who can recognize social needs or economic opportunities and who can conceive and plan will be the men most sought after. They will be the ones who will hire the analysts (engineering scientists), the constructors, and the operators. To a large degree this is true today.

THESIS

The concept ("design") abilities of the student may be developed in at least three ways: (a) through design courses, planned to meet the need directly through lectures and exercises (this is the method used in architecture), (b) by subjects in which design problems are interwoven with the teaching of basic theory, and (c) by sticking to basic theory and the techniques of analysis, letting the student develop his own skill at inventive and conceptual thinking by exposure

The teaching method I have in mind is best understood by studying an actual problem assignment. The example chosen is from engineering thermodynamics.

to the ideas and accomplishments of the great creative scientists.

The teaching of design by method (a) has not been well developed, except in connection with machines, aircraft, and architecture. Method (c) offers little promise for engineering. My thesis is that the second method can and should be more widely used in engineering education.

EXPLANATION

The teaching method I have in mind is best understood by studying an actual problem assignment. The example chosen is from engineering thermodynamics, partly because I teach this subject, but also because thermodynamics is one of the best examples of a subject that is often taught with no element of engineering design. It is a theoretical subject involving many abstract ideas and is normally expected to require rigorous thinking and exact calculations.

ILLUSTRATIVE PROBLEM

The following is a typical problem assignment to juniors about the middle of the first term of a two-term course in chemical engineering thermodynamics.

* * * * * * * * * * * *

Problem 10

A gas well in New Mexico produces essentially pure CO_2 at 800 psia and 100°F. The pressure is reduced to 200 psia by flow through a partially closed ("cracked") valve and delivered by pipe line to a plant several miles away. The flow rate is steady at 10 million ft^3/day (reported as ft^3 at 60°F and 1.0 atm).

The Joule-Thomson expansion through the adiabatic valve causes the gas to cool. This cold gas is used to provide refrigeration for a natural gasoline plant located near the wellhead. The condenser to be cooled operates at 60°F, and the minimum temperature difference for heat exchange is 5°F (i.e., the warmed CO_2 leaves at 55°F).

a) What is the temperature of the CO_2 leaving the valve?

b) What is the attainable refrigeration load, expressed as BTU/hr?

(Comment—note how the instructor has made this sound like a practical problem by the wording. This is pure camouflage—the solution is simple and straightforward. The student is not asked to think—only to know how to use the first law and the Mollier diagram for CO_2.)

Solution

From the book, the first law flow equation is found to be

$$Q - W_n = \Delta h$$

As applied to an adiabatic valve Q and W_n are zero, so the enthalpy leaving the valve is the same as upstream. This is read from the Mollier diagram to be 146 Btu/lb CO_2. At 200 psia CO_2 has this enthalpy at 5°F, which is the answer to (a).

At 55°F and 200 psia the enthalpy is 158 Btu/lb, as read from the chart. In the condenser Δh is 158-146 or 12 Btu/lb CO_2. From the first law flow equation as applied to the condenser

$$Q - 0 = \Delta h$$

so the refrigeration amounts to 12 Btu/lb CO_2 flowing.

The specific volume of CO_2 at 60°F and 1.0 atm is read from the chart as 9.2 ft^3/lb, so the CO_2 flow rate is

$$10{,}000{,}000/9.2(24) = 45{,}300 \text{ lb/hr}$$

The refrigeration load is then

$$45{,}300(12) = 543{,}000 \text{ Btu/hr}$$

This is the answer to (b).

* * * * * * * * * * * *

USE OF THE PROBLEM TO TEACH DESIGN

Now consider the problem so reworded as to invite the student to look at the design aspects of the situation.

The CO_2 flow rate is specified to be the same as before. The pipe line pressure is 200 psia, as before. Cooling water is available which can be used to cool the CO_2 stream to 70°F. The condenser to be cooled now operates at 20°F; the cold gas can be warmed only to 15°F so as to maintain the minimum temperature difference of 5°F.

The student is now asked: how much refrigeration is attainable from the CO_2 stream? How would the necessary equipment be arranged (i.e., draw a flow sheet)?

The routine M.I.T. "A" or "B" student sees the statement regarding available cooling water, notes that the feed gas is the only thing capable of being cooled to 70°F, and so refigures the problem with gas entering the valve at 70°F and 800 psia.

Enthalpy values from Mollier chart: feed gas, 146; gas at 800 psia, 70°F, 126; gas at 200 psia, 15°F, 148. Refrigeration is then

$$45{,}300(148\text{-}126) = 1{,}000{,}000 \text{ Btu/hr}$$

and

$$45{,}300(146 - 126) = 906{,}000 \text{ Btu/hr}$$

are removed by the cooling water. The flow sheet is shown in Fig. 1.

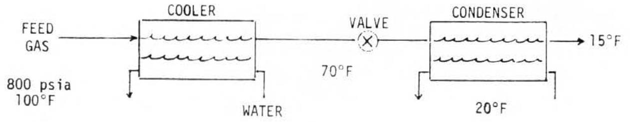

FIGURE 1

A second student, probably a "B" or "C" man, goes through this same calculation, but in doing so notices that the CO_2 leaving the valve is partly liquefied. This is evidently a good thing. If all the CO_2 could be liquefied, there would be a very large amount of refrigeration. But available cooling water limits cooling to 70°F. The chart shows that CO_2 could be liquefied at 70°F if the pressure were about 865 psia. The well pressure is only 800 psia. But it should not take much power to compress the feed gas to 865 psia; the pump might be expensive because of the high operating pressure, but would be physically small because the gas density is high and the volumetric displacement low.

The second student's flow sheet is shown in Fig. 2. The compressor is assumed to operate adiabatically and reversibly, and the pressure change is assumed to be isentropic. The first law gives the flow work as $-\Delta h$, which is read from the chart as approximately 2 Btu/lb. The theoretical power required is

$$45{,}300(2)/3412 = 26.7 \text{ kw} \quad \text{or} \quad 35.6 \text{ hp}$$

which does not seem like much.

The CO_2 now leaves the cooler completely liquefied at 70°F with an enthalpy of only 65 Btu/lb. Δh is zero through the valve, so the refrigeration attainable in the condenser is

$$45{,}300(148 - 65) = 3{,}760{,}000 \text{ Btu/hr}$$

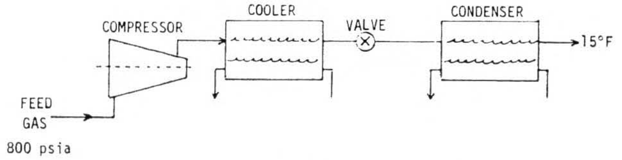

FIGURE 2

The student does not know much about the efficiency or cost of compressors, but he concludes that even if the actual power were twice the theoretical, the compressor installation would appear to be well worth while in view of the very large increase in refrigeration attainable.

A third student follows the same reasoning and makes the same calculations as the second, but is troubled by the fact that the chart gives extremely poor precision in reading the Δh of 2 Btu/lb in the compressor. He has learned that if kinetic and potential energy terms are neglected, Δh for reversible flow is given as

$$-\int v dp$$

Reading the chart, he finds the specific volume

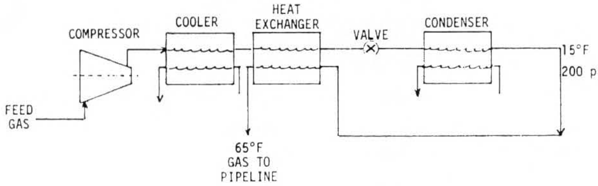

FIGURE 3

of the feed gas to be 0.115 ft^3/lb and that of the gas compressed isentropically to 865 psia to be about 0.105. An average value of 0.11 ft^3/lb cannot be more than 5% in error, so

$$\Delta h = 0.11(865 - 800)(144/778) = 1.32 \text{ Btu/lb}$$

from which he calculates the theoretical (adiabatic reversible) compressor power to be 17.5 kw.

A fourth student makes the same calculations as the second or third student, but hates to see the gas go to the pipe line at 15°F. Cannot this cold gas be useful? Water cooling to 70°F certainly was. Using the cold gas to partially cool the feed gas would only save cooling water. The thing to do, then, is to use the 15° gas to cool the liquid CO_2 leaving the gas-water heat exchanger. His flow sheet is shown in Fig. 3.

Continued on page 164.

TEACHING PROCESS DESIGN

Continued from page 123.

The cold gas is warmed in the heat exchanger to 65°F and leaves with an enthalpy of 161 Btu/lb. Since the mass flow is the same on both sides of the heat exchanger, the enthalpy decrease of the liquid CO_2 is the same as the enthalpy increase of the cold gas, which is (161-148) or 13 Btu/lb. The enthalpy of the liquid going to the valve (and entering the condenser) is now (65-13) or 52 Btu/lb. So the refrigeration is

$$45{,}300\,(148 - 52) = 4{,}350{,}000 \text{ Btu/hr}$$

The student recognizes that the high-pressure heat exchanger might be expensive (he suggests that the high pressure liquid would flow through tubes and the 200 psia gas through the shell) and doesn't know if the extra 590,000 Btu/hr of refrigeration would warrant the cost of this additional piece of equipment (he hopes that he will soon get a course which will enable him to answer such questions).

DISCUSSION

The possible ramifications of this sort of development of a thermo problem are enormous. But this is a course in thermodynamics and must move along—there is a lot more subject matter to cover. The problem has been a good workout in the use of a Mollier diagram and in the application of the first law flow equation to heat transfer equipment and to a Joule-Thomson expansion, as well as the calculation of isentropic compression power. The calculations are simple so as not to divert the student from the ideas introduced. Elementary concepts of process design are encountered (possibly for the first time), and the student has an opportunity to invent and compare alternative process schemes. There is a continuous feedback from analysis to better design.

There are many angles which can be developed in the discussion. The book and the course lectures have seemed to suggest that reversible processes are highly desirable. What are the irreversible features of the fourth student's flow sheet? Can they be reduced or eliminated? Can the common work functions ("availability") be used to calculate the operation of a wholly reversible process. Can a completely reversible process be described? Could an expansion engine be employed? Could the heat exchangers be made reversible, even with a zero temperature difference at one end? Is counter-current flow in the exchangers desirable or necessary? What is the origin of the stipulation of a 5°F minimum temperature difference? The second student found the high pressure gas to liquefy partially in passing through the valve. Is this phenomenon peculiar to CO_2? Could the book formulas for the Joule-Thomson coefficient be useful? What experimental procedures were employed to get the data on which the Mollier chart is based? If we had had no chart, could we have made useful calculations? Could we make a similar analysis for the case of a natural gas well (pure methane; or 90% methane, 10% ethane)? Would it be better to use a separate ammonia refrigeration plant, or possibly some combination of ammonia refrigeration plus Joule-Thomson expansion of the gas stream? Where would cooling water come from in New Mexico? What are water cooling towers and how do they work? Why 200 psia in the pipeline? Etc., *ad infinitum.*

DIFFICULTIES OF THIS APPROACH

The possibility of introducing design thinking into theoretical subjects depends primarily on the interest and competence of the instructor. It *can* be done, for some M.I.T. instructors have been doing it for years. My department's most successful teacher, Dr. W. K. Lewis, has done this sort of thing all his life. Students in engineering generally like the approach and find that it helps them greatly to understand the theory.

The instructor who worries continually about the things he must "cover" hesitates to "take the time out" for this sort of discussion. Instructors often lack the practical engineering background to do it successfully. Such background (and material for good problems) often comes from high-level *engineering* consulting work. The rise of engineering science and the increased consulting work by younger staff members may have resulted in most of the staff's consulting being devoted to the more scientific "analysis" kind of activity, rather than to engineering design. It might even be suspected that only about half of the M.I.T. engineering staff are true engineers in the sense of being competent in design, and that the fraction is getting smaller. The most important single thing M.I.T. can do to improve the instruction in engineering design is to engage more instructors who are enthusiastic about the subject and who have not yet become so enamoured of engineering science that they have lost interest in design. □