RECYCLE WITH HEATING

A Laboratory Experiment

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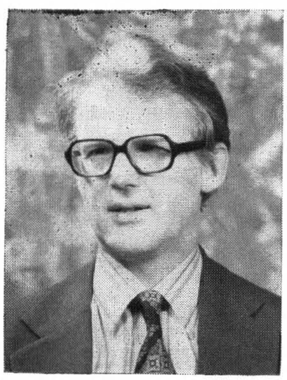
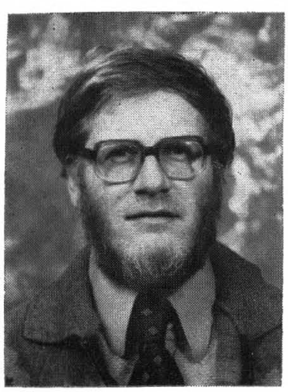
SOME OF THE BASIC methods of chemical engineering (heat and mass balances, for example) have analogies (such as money) in everyday life, and freshman students rarely have any conceptual difficulty when such basic ideas are introduced. However, when heat and mass balances are combined with recycle, students often have difficulty in analysing the process. They have difficulty not so much with the heat and mass balances themselves as with the whole concept of the recycle process. This is mainly because there is no immediate everyday counterpart, although analogies can be attempted with taxis and people.





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In order to aid the understanding of recycle we have devised a simple apparatus in which water is heated in a recycle loop. When operated in the steady state, the apparatus permits both a visual and an experimental appreciation of the operation of a simple recycle loop. Moreover, in the unsteady state the apparatus has a response time of ten minutes or so, and thus, transient behaviour can be followed easily. The apparatus is relatively simple, and since it is built from domestic plumbing pipes and fittings it has a familiar and easily grasped appearance. It is mounted on a wallboard so that the flow path can be seen at once. It uses only water and electricity as consumables.

APPARATUS

Fig. 1 is a schematic diagram of the apparatus. The recycle is driven by a domestic central heating pump of the type used to circulate water around radiators. Ours is an SMC Commodore and it consumes about 150 watts. The heater is a modified instantaneous shower heater, in essence a copper can containing a 3kW heating element. The shower heater originally had two in-built safety devices, one a water pressure switch and the other an anti-scald thermal cut-out. The heater could only be activated when there was pressure (and hence water) in the can and the temperature was below 50°C. We modified our heater to increase the cut-out temperature to 80°C and removed a flow constriction in the pressure-sensing circuit.

The pump drives the recycle at up to 8 litres/

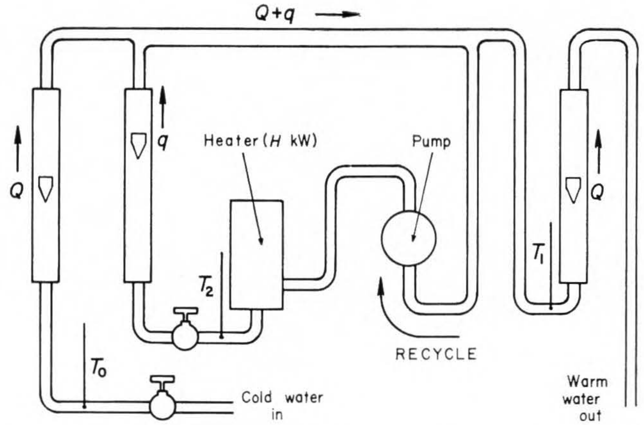

FIGURE 1. Schematic diagram of the apparatus. The inlet flow, Q (maximum 3 litres/min), is ordinary mains water. A recycle loop, flow q (maximum 8 litres/min) is driven by a pump through a domestic shower heater (3kW). The temperature of the inlet water, the outlet water and just after the heater in the recycle loop, are all measured.

min, the highest reading of the recycle rotameter. There is a rotameter (3 litres/min maximum) on the inlet side measuring the inlet flow of tap water and an identical one on the outlet side. Mercury-in-glass thermometers (although digital devices would be better) are used to measure the water inlet temperature, the temperature after the heater in the recycle loop and the outlet temperature. The water flow rate of the feed and also of the recycle loop may be adjusted and set by means of valves. The complete rig is illustrated in Fig. 2.

The tube sizes, although apparently arbitrary, make a difference to the performance of the apparatus. Air comes out of solution in the heater and tends to accumulate in the pump which is working here at less than its design flow. By using 28 mm tubing at a slightly rising angle for the top tube of the recycle loop and 22 mm tube for the descending tube to the pump, the air tends to enter the outlet pipe rather than be carried downwards. In the 15 mm sections air bubbles are easily carried along, either upwards or downwards.

EXPERIMENTS

Steady-State

Mass balances: The first experiment is trivial but is a graphic illustration of the mass balance principle: at various valve settings it is easy to show that whatever the recycle rate the inlet flow rate always equals the outlet flow rate.

Heat balances: *a*) With the heater switched on and at a fixed input water flow rate, the apparatus shows that the outlet water temperature is independent of the recycle rate. Students often find this observation disconcerting. They observe a change in the temperature of the recycle water when its flow rate is altered, but find that the outlet temperature of the loop remains the same. Only when they consider the overall heat balance do they find it obvious that the outlet temperature is unaffected.

b) Using the variables marked on Fig. 1 for flows and temperatures for the steady-state, a heat balance over the whole system shows that

$$T_1 = T_0 + (H/QC) \qquad (1)$$

where H is the combined heat input of the pump and heater and C is the specific heat capacity of water.

Similarly one obtains

$$T_2 = T_0 + (H/QC) + (H/qC) \qquad (2)$$

from a heat balance across the shower heater, after eliminating T_1 by means of Eq. (1).

So, by measuring the outlet water temperature, T_1, as a function of the through flow rate, Q, it is possible to determine the combined heat input of the heater and pump by the use of Eq. (1). The experiment takes some time to perform because it takes about fifteen minutes for the steady-state to be reached after a change in flow rate. By plotting $(T_1 - T_0)$ against $1/Q$, the gradient (H/C) gives the power input (H) as shown on Fig. 3. Alternatively, Eq. (2) can be used. In

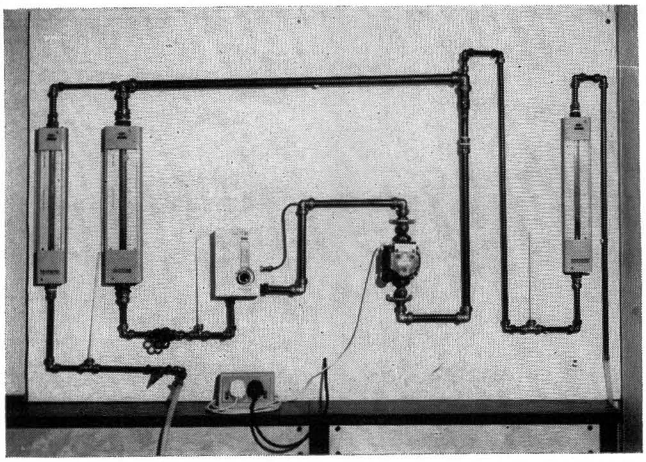

FIGURE 2. A photograph of the apparatus. It is mounted on a wall board so that the flow directions are obvious. The top pipe is slightly angled to assist in purging the air which comes out of solution as the water is heated.

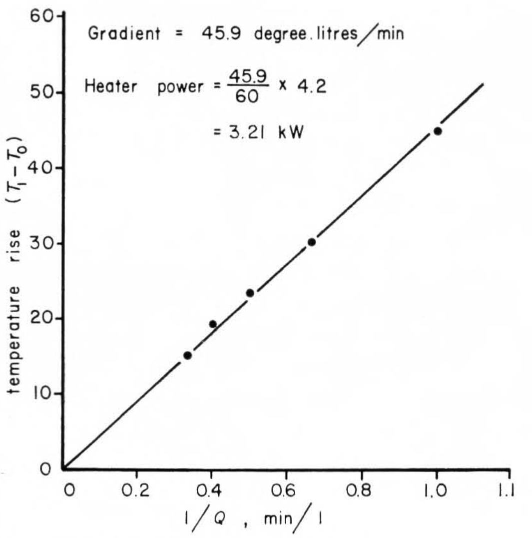

FIGURE 3. Results from the steady-state operation of the apparatus. The temperature rise of the through stream is plotted against the reciprocal of the through flow rate. The graph is a straight line through the origin with a gradient determined by the combined energy input of the heater and circulating pump.

this case T_2 is plotted against 1/q, where q is the recycle rate, and H is obtained from the same gradient. This latter method has the advantage of actually making use of the recycle flow.

Unsteady-State

In unsteady-state experiments both the inlet flow and recycle flow are fixed, the system is allowed to approach, but not necessarily reach, equilibrium, and the heater is switched either on or off as appropriate. The apparatus takes several minutes to respond and the dynamic changes can be monitored by hand. Typical examples of temperature-time graphs are shown in Fig. 4 for both rising and falling temperature. The recycle rate was 5 litres/min and the inlet flow rates 1.0, 1.5, 2.0, 2.5, and 3.0 litres/min.

A heat balance on the system for a small time interval, dt, in which the outlet temperature, T, changes by dT gives

$$QCT_0 + H = QCT + VC\ (dT/dt) \qquad (3)$$

where V is the volume of the recycle circuit which, as an approximation, is assumed to be perfectly mixed. Using Eq (1) to eliminate H, and then integrating from T_0 at time 0, gives

$$\ln\left[(T_1 - T)/(T_1 - T_0)\right] = -Qt/V \qquad (4)$$

T thus rises exponentially to the steady-state temperature T_1 when the heater is switched on

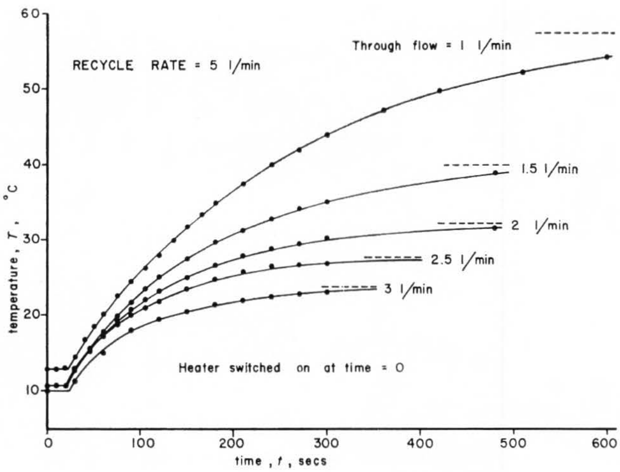

FIGURE 4(a)

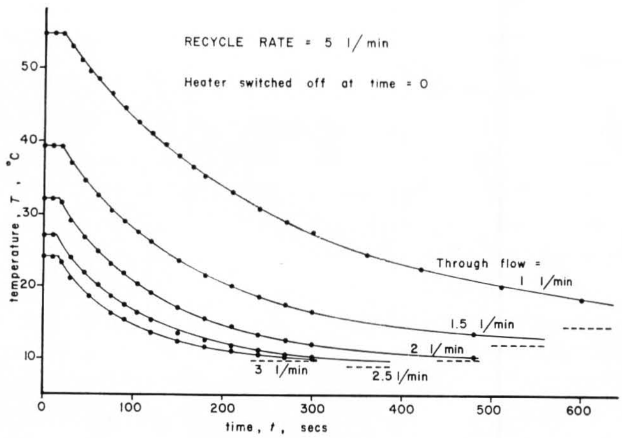

FIGURE 4(b)

Figure 4. Results from the unsteady-state operation of the apparatus. The recycle rate was fixed at 5 litres/min and the response is only slightly dependent upon it. Fig. 4(a) shows the effect of switching the heater on at different through flow rates. Fig. 4(b) shows the effect of switching the heater off at different flow rates. The temperature rises in Fig. 4(a) and falls in Fig. 4(b) exponentially to the limiting temperature. The different limiting temperatures in Fig. 4(b) are caused by the heat input from the recirculating pump and also by small changes in the feed water temperature. Note that the response time is a function of the inlet flow rate.

and falls exponentially to the temperature T_0 when the heater is switched off. The time constant is independent of the heater power and also of the recycle rate but depends on Q, the inlet flow rate, and the volume of the system. By plotting the log arithmetic term of Eq. (4) against time, the gradient (-Q/V) can be determined. If this is repeated for several flows then a graph of these gradients against Q gives a straight line of slope 1/V through the origin.

The volume of the recycle circuit so determined is only an effective volume rather than a

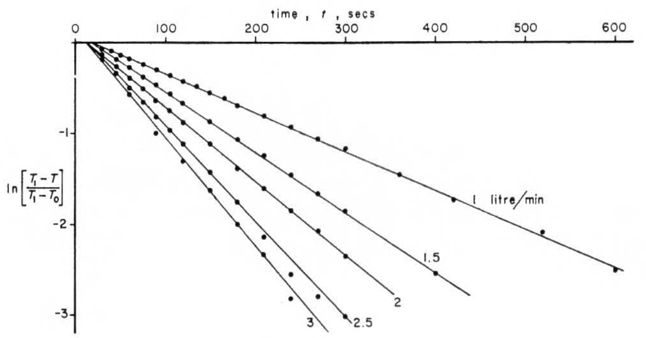

FIGURE 5. Logarithmic plots of the results of Fig. 4(a).

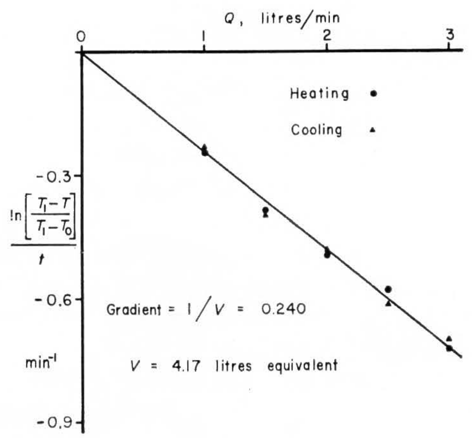

FIGURE 6. The effective volume of the recycle system determined from the gradients of the lines in Fig. 5 by plotting the gradient against the through flow rate. Values from the curves of Fig. 4(b) are also shown although the straight line logarithmic plots have not been reproduced.

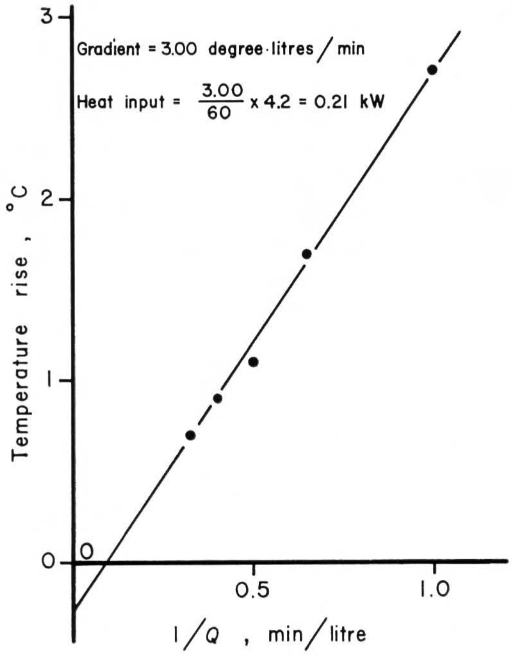

FIGURE 7. The temperature rise of water passing through the system obtained from the limiting temperatures of the cooling curves. (Fig. 4(b)) and the feed temperature plotted against the reciprocal of the through flow rate. This graph is equivalent to the steady state results of Fig. 3 but with the only heat input coming from the energy of the pump. The slight offset of the line from the origin is most likely caused by a systematic error between the two separate thermometers which were used to measure the temperature rise.

true internal volume because the metalwork of the system behaves as a heat sink. Its effect is quite large because the pump weighs several pounds but conduction is fast enough for the metal and fluid in the recycle loop to have the same temperature. The temperature profiles of Fig. 4 demonstrate that, as predicted by Eq. (4), the system reaches equilibrium faster for higher inlet flow rates than it does for lower inlet flow rates.

Figure 5 shows the straight lines given by Eq. (4) for rising temperature using the typical data given in Fig. 4. Note that there is a delay of between 10 and twenty seconds before the thermometer responds to the heater being switched on, due to the transit time of the water in the pipes. Fig. 6 shows the gradients of the lines of Fig. 5 plotted against Q, the inlet flow rate, and it is from the gradient of Fig. 6 that the effective volume, V, of the recycle loop can be determined.

REFINEMENTS

The analysis of the behaviour of this apparatus is straightforward. The accurate interpretation of actual experimental results is not so simple because of drift in the temperature of the water feed and other small effects. Rough and ready results and analysis may be adequate for routine teaching, but to get the best from the apparatus a more refined approach is necessary. For example it is better to extrapolate the dynamic experimental data to obtain the steady-state temperatures. This gives students useful practice in analysing an exponential rise to a limit as well as giving the steady-state temperatures more accurately. The falling temperature curves give limiting temperatures which, because of the heat input from the recycle pump, are not equal to the inlet water temperature T_0. Indeed the temperature rise between the inlet water temperature and the extrapolated outlet water temperature with the heater switched off can be used in a heat balance to determine the energy input by the pump. Fig. 7 shows ΔT, the temperature rise of water through

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into the final text.

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the apparatus, plotted against 1/Q. The energy input of the pump is found from the gradient to be about 210 watts. The intercept (about 0.3°C) probably represents the scale reading difference between the two thermometers.

A further refinement that is possible with the apparatus is to run the dynamic experiment in the limiting case of recycle with no through-flow. With no through-flow the apparatus is analogous to a well-mixed batch reactor, whereas it is analogous to a CSTR when through-flow is present. Fig. 8 shows results for this case for three different recycle rates. The three lines do not coincide because different starting temperatures were used. The results show that after 30 seconds or so there is, as expected, a linear temperature rise with time. The temperature rises with no limit at least until the safety cut-out of the shower heater operates. The gradients of the lines on Fig. 8 are all the same and by using the combined heater and pump energy input of 3.21 kW it is possible to estimate the effective recycle volume. This is 3.95 litres for the results shown, about 5% less than the value obtained using the through-flow method. The most likely cause is the time taken to heat up parts of the metalwork of the pump; this experiment lasts only four minutes, compared to ten for the through-flow method.

Students always say that the apparatus could be improved by lagging the pipework to reduce heat losses, but simple measurements on a cooling curve indicate that the heat losses are very small. Also, for some of the temperature response

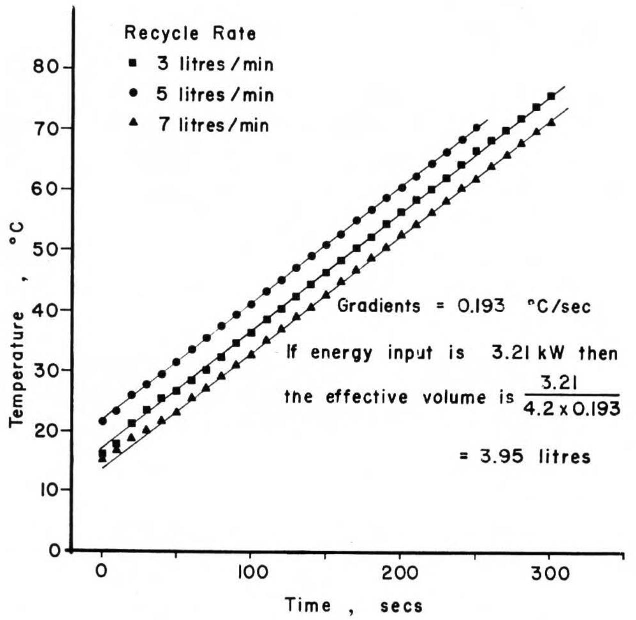

FIGURE 8. With no through flow the recycle loop temperature rises without limit as can be seen above. Using the combined energy input of the heater and pump (determined on Fig. 3) the effective volume of the recycle loop can be determined using the gradient of the lines. This volume can be compared with the value determined on Fig. 6 (4.17 litres equivalent). The lines are for different recycle rates which, as expected, have no effect. Different initial temperatures were used. Up to the first minute it can be seen that the system is not well-mixed.

curves the water temperature is below the ambient air temperature and so the system is gaining heat rather than losing it.

CONCLUSION

Our apparatus has been in service for several years without giving trouble, perhaps a consequence of using well proven domestic components. The recycle experiments performed with it can range from simple mass and heat balances right through to the dynamics. Its main purpose, however, is to provide a vivid demonstration of basic mass and heat balances in a system with recycle. □