UNSTEADY-STATE HEAT TRANSFER FROM A STEAM-HEATED COIL TO A TANK OF WATER

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As a response to the Finneston report[1] that recommended more practical, industry-related experience in undergraduate degree courses, a series of experiments related to industrial practice has been introduced for first-year students. One such experiment, which can also be used as an unsteady-state heat transfer experiment, is the primary object of this paper.

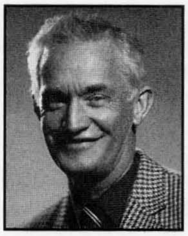
At Loughborough students receive lectures on heat transfer in the second semester of their first year at the university (the first semester introduces fluid mechanics). These lectures expand on and develop the university entrance ('A'-level) examination syllabus in physics. With this course and other experiments on heat transfer in the first-year laboratory, they thus receive a solid foundation in this subject.

The experiment consists of heating a tank of water with an immersed steam-heated coil, a common chemical engineering operation. The temperature of the water is measured as it varies with time and, simultaneously, the condensate formed is collected.

As a practical-experience experiment, it shows the use of pressure reducing valves, steam traps, and strainers. The strainer and the steam trap (a floating ball type) are stripped down to show how they function, sketches are drawn of the "internals," and the strainer and trap are reassembled. Locking off the steam reducing valve and using a "permit to work" are included in the procedure, similar to industrial practice. Other types of disassembled steam traps are on display by the rig. Postgraduates assist in supervising the undergraduates.

EQUIPMENT

Figure 1 is a line drawing of the steam lines. The coil enters and leaves through the top of the tank. It consists of a 186-cm long, 1/2-in outside diameter copper pipe formed into two complete vertical coils on a 16.5-cm diameter. The coils are "open," with approximately 5 cm between loops. The equivalent surface area for heating is 0.073 m^3, based on outside diameter. The coil is approximately at the geometric center of the tank, which has an18-in square (47 cm square) base by 15-in (38 cm) high. The tank is made isenthalpic by having 4-cm thick expanded polystyrene sheets on all sides, including the base and top. A mercury-filled thermometer with a 6-in diameter dial was used to monitor the temperature change. The bulb of the thermometer was positioned at the geometric center of the liquid in the tank.



Peter Rice *spent twenty-one years in industry after leaving school at fifteen years of age. He received his Master's degree from Cranfield and his PhD from Loughborough (at age 40), where he has spent the last twenty-five years as lecturer and senior lecturer. His interests are in heat and mass transfer, especially in food processing, and with phase change also in physical property prediction.*

PROCEDURE

We asked the students to add enough cold water to make 70 liters in the tank, which results in a beginning water temperature of about 15 °C. The main steam valve was opened and steam passed through a by-pass to waste. This clears any condensate present in the supply line. The steam main pressure was 9 barg and was reduced to 1 barg through the reducing valve. The steam was wet, so the pressure reading could be used to estimate the steam temperature.

The steam pressure was read on a calibrated Bourdon gauge. The valve allowing steam to the coil was opened and the steam passed through a strainer, a sight glass, an electronic sensor for pressure, and then through the steam trap. At this point the steam trap by-pass was open and the two-way valve directed any condensate to waste.

When the water reached 25 °C, the steam trap by-pass was closed and the two-way valve was turned to direct the condensate into a preweighed drum. A stopwatch was also started at this point. Then time was recorded at 5°C-temperature

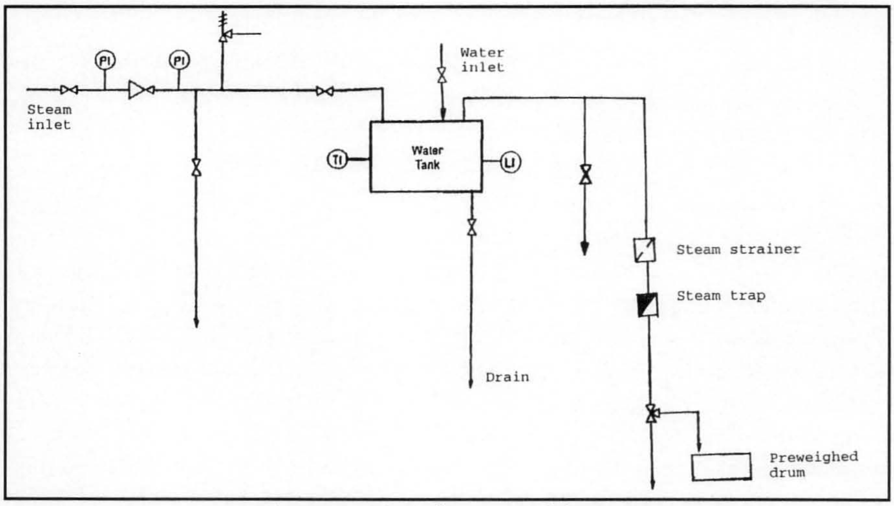


Figure 1. *Flow diagram of the system.*

The experiment consists of heating a tank of water with an immersed steam-heated coil, a common chemical engineering operation. The temperature of the water is measured as it varies with time and, simultaneously, the condensate formed is collected.

intervals until the temperature reached 75°C. At that time the two-way valve was turned to again direct the condensate to waste, the valve directing the steam to the coil was closed, and the steam valve was turned and "locked off." The bypass valve was opened and the main steam supply valve was then closed. The condensate collection drum was then weighed and the amount of accumulated condensate was found.

At this time, a "permit to work" was obtained from the laboratory supervisor, who checked the equipment for safety prior to issuing the permit. The steam trap and strainer were stripped, sketches were made of their internal structures, and the equipment was reassembled. The permit was countersigned to indicate safe completion of the work. The mass of water heated was recorded from a calibrated sight glass fixed on the side of the tank.

UNSTEADY-STATE MODELING

A simple heat balance at some time t gives

$$MC_p \frac{dT}{dt} = UA\left(T_s - T\right) \tag{1}$$

where

M	mass of water being heated
C_p	specific heat of water
A	area of coil for heat transfer
T_s	steam temperature (set by steam pressure)
T	water temperature at time t
U	overall heat transfer coefficient

We note that since the steam side condensation coefficient (of the order of 14,000 $Wm^{-2}K^{-1}$) is so much greater than the liquid side coefficient, we can assume that U is, essentially, the liquid side coefficient.

Integration using the initial condition that at t=0, $T=T_i$, the water temperature at the beginning of the experiment (25°C in our case), gives an exponential temperature-time relationship of

$$T = T_s - \left(T_s - T_i\right) \exp^{(-t/\tau)} \tag{2}$$

or

$$t = \tau \ell n \left(\frac{T_s - T_i}{T_s - T} \right) \tag{3}$$

where

$$\tau = \frac{MC_p}{UA} \tag{3a}$$

The time constant, τ, describes the shape of the curve, *e.g.*, whether the temperature change is fast or slow. As will be shown later, a reasonable fit of the data is obtained.

The heat loss, however, is by natural convection on the liquid side, and noting that for natural convection

$$Nu = f(Gr\,Pr)^{0.25} \tag{4}$$

where

Nu	Nusselt number
Gr	Grashof number
Pr	Prandtl number

we set

$$U = U'\left(T_s - T\right)^{0.25} \tag{5}$$

The heat balance is then

$$MC_p \frac{dT}{dt} = U'A\left(T_s - T\right)^{1.25} \tag{6}$$

which, on integration and using the initial condition that at t=0, $T=T_i$, as before, results in

$$t = \frac{MC_p}{0.25\,U'A} \left(\frac{1}{\left(T_s - T\right)^{0.25}} - \frac{1}{\left(T_s - T_i\right)^{0.25}} \right) \tag{7}$$

or

$$T = T_s - \left(\frac{1}{\left(\frac{0.25\,U'At}{MC_p} \right) + \frac{1}{(T_s - T_i)^{0.25}}} \right)^4 \qquad (8)$$

As will be seen, a better fit of the data results by using Eq. (8).

To describe the temperature variation with time, U and U´ have to be known. This is done by using the time at temperature T=60°C to evaluate U and U´ and then using these values to predict the rest of the curve. It is possible to carry through a multi-regression and obtain values for U and U´ which minimizes the least squares deviations with the experimental points, but this is just an exercise in numerical methods and does not give a better insight into the heat transfer process.

APPLICATION TO THE EXPERIMENT

Two steam pressures (Case 1 and 2) were used: 130°C (1.7 barg) and 121.3°C (1.07 barg). The corresponding masses of water heated by the coil were 65 kg and 69 kg, respectively. The mass of condensate collected in each case was 6.56 kg and 6.8 kg, respectively. The initial (starting) temperature was 25°C, and the specific heat was taken as 4.19 kJ $kg^{-1}C^{-1}$ (a mean value over the present range of temperatures).

RESULTS AND DISCUSSION

The calculated values from the data for U, corresponding to the two steam temperatures, were 5795.2 and 4303 $Wm^{2}C^{-1}$, respectively, while the values of U´ were 2022 and 1455.2 $Wm^{-2}C^{-1.25}$, using the 60°C experimental value. With these values of U and U´, the theoretical results presented in Figure 2 were calculated. Both models give good fit to the experimental data, with correlation coefficients of 0.9985 and 0.9990 with U, and 0.9994 and 0.9998 with $U'\Delta T^{0.25}$ for the two cases. The $U'\Delta T^{0.25}$ model fit of the data is slightly better, as can also be seen from Figure 2.

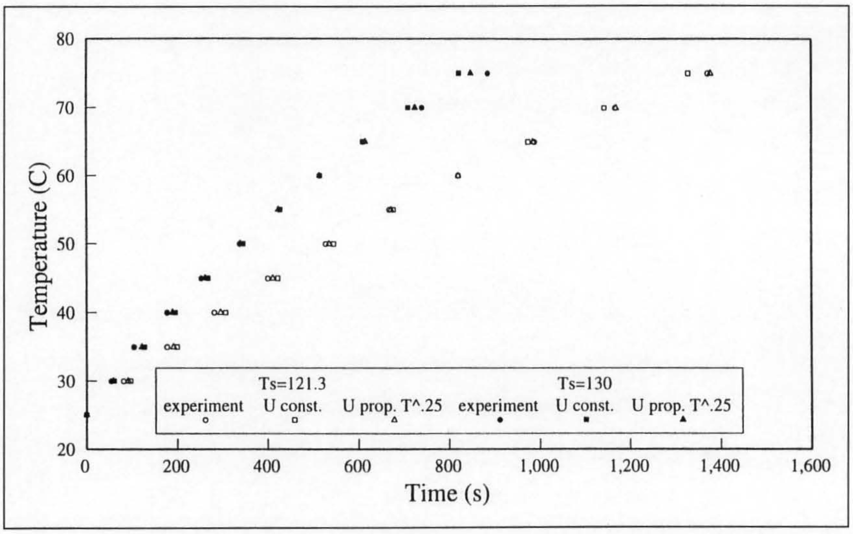


Figure 2. *Comparison of variation of measured and predicted temperatures with time.*

Although the use of steam-heated coils is a common operation and is widely used in chemical engineering, there is little information on their performance. Inglesant and Storrow,[3] reporting results on heat transfer using cooling coils in tanks, suggest a value of 0.73 in place of 0.53 (Fraas[2]) for C in the ($Nu=C(GrPr)^{0.25}$) relationship used to describe free convection from a horizontal cylinder. Even using this value of C, the size of U is still considerably less than the measured values, as one would expect comparing a horizontal cylinder with a cylinder formed into a vertical coil.

We report[4] results for an 18-cm diameter, $1\frac{1}{2}$-loop steam-heated closed-loop coil (area of 0.061 m^2) positioned similarly to the present experiments, but with the loop cross-section oriented horizontally. A value for U of 2325 $Wm^{-2}C^{-1}$ was obtained by using steam at 120.3°C.

The reason for this difference in heat-transfer coefficient values is that within the tank confines, a strong recirculatory flow is set up due to the convection currents. This causes an enhanced free-convection type heat transfer. The two heat-transfer coefficients corresponding to the two driving temperature differences used in the experiments indicate different enhancement factors (*e.g.,* different recirculatory flows) with the more intense recirculation created by the higher steam temperature, as would be expected.

In the case of the results reported in [4], the recirculation is less vigorous due to the coil orientation compared to the present results. To complete the results for the laboratory experiment, we calculate as follows:

Case 1 Steam dryness $= MC_p\Delta T / mh_{fg} = 0.96$, where m is the mass of condensate collected and h_{fg} is the latent enthalpy (2174 kJ kg^{-1} at 1.7 barg)

Case 2 Steam dryness = 0.97 (h_{fg}=2200 kJ kg^{-1} at 1.07 barg)

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Exorcising Maxwell's Demon

Continued from page 95.

tion is associated with the entropy of information, there would still have been a complete conversion of heat into work. Szilard offered no details concerning the manifestation of this entropy change.

THE THERMODYNAMICS OF COMPUTING

Despite the exposure by Jauch and Báron of the flaw in Szilard's engine, work dedicated to saving the second law has continued apace, with the computer now assuming the role of savior. Instead of the "corrective" kln2 entropy units being assigned to information acquisition, the idea has now been advanced that these units of entropy must be assigned to memory erasure.[5] This is purported to be the entropy change accompanying the thermodynamically reversible erasure of one bit of information.[6] The argument proceeds by stating that a measurement in the one-molecule heat engine can be made reversibly (no creation of entropy) but after the completion of a cycle the demon must reset its memory at a cost of kln2 units of entropy increase in the surroundings due to heat dissipation. As the work of Landauer[6] forms the basis for this explanation, it will now be subjected to a critical review.

Mixing ideas from thermodynamics, statistical mechanics, and information theory, Landauer obtained an expression for the minimum energy dissipation in a computer. His system was an assembly of N bits, each of which could occupy either a *zero* or a *one* state. He assumed each state to have the same entropy and considered a restore-to-*one* operation where the bits, initially randomized with regard to state, were all set to *one.* Arguing that the number of states available to a bit had been reduced from two (either *zero* or *one*) to one in the process, he reasoned that the entropy of each bit would be reduced by kln2. He continued by stating that the entropy decrease of a bit must be compensated by heat dissipation to the surroundings of at least kln2. Despite disclaiming a reliance on information theory, Landauer obviously views the entropy change of kln2 per bit in this context.

Landauer is not justified in assigning an entropy change to the process of restore-to-*one*. Although he provides little explanation, he seems to be applying methods of statistical mechanics, not at the molecular level but to a system comprised of N *macroscopic* subsystems, the bits. Not only is this procedure questionable, but the process considered has no thermodynamic significance. Landauer's restore-to-*one* process involves macroscopic subsystems, and his calculated entropy change is akin to that which might be imagined to accompany rearrangement of pieces on a checkerboard.

As a macroscopic subsystem, each bit will exhibit a set of intensive properties which will depend only on the state-determining intensive variables (*e.g.,* temperature and magnetic-field strength) as specified by the phase rule. In terms of intensive properties, each bit behaves as if it alone were present and oblivious of the identity of its neighbors, as, for example, would be the case for a collection of crystals. Because Landauer set entropies equal for states *zero* and *one*, there can be no thermodynamically significant entropy change in going between any two spatial configurations of *zeros* and *ones*. Of course, if the transition between states is not carried out reversibly, as would be expected of a computer, heat dissipation to the surroundings will account for the necessary entropy increase of the universe.

Landauer seems to view kln2 as the information entropy of a bit. But, as has been convincingly shown by Denbigh and Denbigh,[10] information entropy does not reduce to thermodynamic entropy. Landauer's association of heat dissipation with the kln2 term is therefore inadmissible.

For Landauer's assumption of equal entropies for states *zero* and *one*, a legitimate thermodynamic analysis shows that there would be no entropy change in the surroundings from a thermodynamically reversible resetting of memory. This would contribute no additional entropy changes to the analysis of Szilard's engine, but as we have seen, none is needed.

CONCLUSION

The one-molecule heat engine is a flawed thought experiment and therefore cannot provide thermodynamic justification for an entropy of information or an entropy of erasure. Neither of these "entropies" is appropriate in an entropy balance and neither is necessary to save the second law from the assault of Maxwell's demon. With the demise of the one-molecule heat engine, the long and laborious exorcism of Maxwell's demon should be complete.

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