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THE ECONOMIC ADVANTAGES OF ACCURATE TRANSPORT PROPERTY DATA FOR HEAT TRANSFER EQUIPMENT DESIGN

The technical and economic consequences of the uncertainties in the estimation methods currently used in Chemical Engineering for transport properties of fluids to process plant design and operation are assessed.

This assignment is carried out by means of specific examples of one heat exchanger and one condenser design.

It is shown that the uncertainties in the transport coefficients which result from commonly used estimation procedures have a significant effect upon the overall technical design of heat exchange equipment. In turn these effects contribute to the necessary capital expenditures on the items of plant. It is demonstrated that such expenditure would be considerably reduced by more reliable estimation procedures based upon accurate experimental data for the transport coefficients of fluids.

1 — INTRODUCTION

We have shown in previous work that at present the transport properties of many fluids must be estimated by methods which depart considerably from the ideal and that therefore the data generated are burdened with large uncertainties [1]. We have also shown that the uncertainties in the transport coefficients which result from commonly-used estimation procedures have a significant effect upon the overall technical design of heat exchange equipment and may result in unnecessary capital expenditure [2]. Although many workers in the field of transport properties have already noted that a knowledge of these properties is significant for process plant design [3-6], there seems to have been no systematic discussion of how significant accurate values of these properties are in quantitative technical and economic terms. This paper is devoted to a study of this type in order to illustrate the need for improved estimation techniques and more accurate experimental measurements. In order to carry out this program we have chosen to study the effect of uncertainties in fluid properties upon the design of heat exchange equipment. In a preliminary paper [2], we discussed two types of heat exchanger (shell and tube and double pipe). Here, we extend our treatment to condensers. In the interests of brevity we report here only the results obtained for one heat exchanger and one condenser since those results obtained for any particular item of equipment are qualitatively similar.

2 — THE METHODOLOGY

The aim of our calculations will be to evaluate the changes in the design parameters of a heat exchanger or a condenser which arise solely from changes made in the transport coefficients of the fluids involved in the process. We then identify these changes in the transport coefficients with possible uncertainties in the values employed for a design. The degrees of freedom of a heat exchanger and condenser may be reduced to two by selecting a specific type of device and by prescribing its duty to satisfy the external constraints of a particular process. We are then left with the heat transfer area and the pressure drop across the fluid ducts. Because this last effect is not usually a major factor

in the design of a heat exchanger or condenser, we shall adopt the heat transfer area as the sole factor that reflects the changes in the design arising from the changes in the transport coefficients of the process streams. The reduction of the numbers of parameters necessary to define the design in this way has the added advantage that the economic consequences of changes in the design are readily estimated.

A second simplification is afforded by the adoption of a standard methodology for the evaluation of the heat exchange area. Since any reasonable design incorporates the physical properties of the fluid streams into correlations for the heat transfer coefficients we are free to use any one of them [3]. In accord with the aims of this paper we adopt one of the simplest.

In the case of shell and tube exchangers we employ the correlation of SIEDER and TATE [7] for the heat transfer coefficient on the inside of the heat exchanger tubes. Denoting this coefficient, referred to the inside tube area, by h_i the correlation reads

$$\frac{h_i D_i}{\lambda} = 0.027 \text{Re}^{0.8} \text{Pr}^{1/3} \left(\frac{\mu}{\mu_w} \right)^{0.14} \quad (1)$$

where the Reynolds number, Re , is $D_i G / \mu$ and the Prandtl number, Pr , is $\mu C_p / \lambda$. Here, D_i represents the internal diameter of the tubes, λ the thermal conductivity of the fluid, μ its viscosity and C_p its heat capacity, all evaluated at the mean bulk temperature of the fluid. G represents the mass flux in the heat exchanger tubes and μ_w the fluid viscosity at the temperature of the wall.

The heat transfer coefficients on the shell side of the heat exchanger tubes, referred to the outside tube area, h_o , is given by the correlation

$$\frac{h_o D_e}{\lambda} = 0.36 \text{Re}^{0.55} \text{Pr}^{1/3} \left(\frac{\mu}{\mu_w} \right)^{0.14} \quad (2)$$

D_e being the equivalent diameter for the shell (D.Q. Kern, 1950).

For horizontal condensers, the average heat transfer coefficients can be evaluated from the correlation [8]

$$h = 1.5 \left(\frac{4G'}{\mu_f} \right)^{-1/3} \left(\frac{\mu_f^2}{\lambda_f^3 g} \right)^{-1/3} \quad (3)$$

where the subscript f refers condensate properties evaluated at the temperature of the film formed, g is the acceleration due to gravity and G' is the condensate loading.

The overall heat transfer coefficient, U_o , referred to the outside tube area for the heat exchanger and to the total surface area required for the condenser, is then calculated from the equation

$$\frac{1}{U_o} = \frac{D_o}{h_i D_i} + \frac{1}{h_o} + R \quad (4)$$

where D_o is the outside tube diameter and R represents the combined resistance of the tube wall and any scale.

Finally, the heat transfer area, A_o , is obtained from the prescribed duty of the exchanger Q , according to the equation

$$Q = U_o A_o (\Delta T)_{lm} \quad (5)$$

where $(\Delta T)_{lm}$ is the corrected logarithmic mean temperature difference for the process streams.

Equations (1) to (5) demonstrate how the transport properties of the fluids will influence the calculated heat exchanger area and so the length of the heat exchanger. It is clear that of the fluid properties is the thermal conductivity which is the dominant factor in the determination of the heat transfer area. It is noteworthy, that it is just this property which is the most difficult to estimate accurately [1].

SAMPLE CALCULATIONS

We consider here two examples from our calculations; first a gas-liquid heat exchanger, and secondly a horizontal condenser for a mixture of gases. The heat exchanger involves the cooling of dry ammonia gas from a compressor with water before passage to a reactor. The exchanger selected is of the baffled shell and tube type, with one shell pass and eight tube passes, and contains 364 tubes (2.44 m long, OD = 3/4 inch, 16 BWG) mounted in a triangular arrangement. The condenser involves liquefaction of a five component vapour mixture of light hydro-

carbons taken from a distillation column. Again the coolant employed is water. The horizontal condenser chosen has one pass in the shell side and four tube passes and contains 774 tubes (4.88 m long, OD = $\frac{3}{4}$ inch, 16 BWG) mounted in a triangular arrangement.

For each of these exchangers the transport properties of the fluid streams have first been assigned reasonable reference values. Subsequently the reference heat transfer area for each exchanger has been evaluated. The results obtained were $(A_o)_r = 53.79 \text{ m}^2$ for the heat exchanger and $(A_o)_r = 137.22 \text{ m}^2$ for the condenser (condensation + subcooling). It should be emphasized that these figures constitute our arbitrary reference values for subsequent calculations, rather than any optimized design.

The next stage in our calculation involves the perturbation of the assumed values for the transport coefficients of the fluids, about their reference values by amounts corresponding to likely uncertainties in the data [1]. The changes in the calculated heat transfer area from the corresponding reference area have been determined as functions of the changes in the transport coefficients for both items of equipment. The value of R has been assumed constant throughout and equal to the equipment design requirements ($R = 0.007$ and $R = 0.004$ respectively). Furthermore, the properties of water have not been perturbed since they have been assumed to be known exactly.

RESULTS AND DISCUSSION

Fig. 1 contains plots of the deviation of the calculated heat transfer coefficients $(h)_c$ from the reference condition $(h)_r$ for the shell side of the exchanger. The change in the thermal conductivity is plotted along the abscissa whereas the change in the viscosity is shown as a parameter of the curves. Fig. 2 contains a plot of the deviations of the calculated area of the heat exchanger $(A_o)_c$ from the reference one $(A_o)_r$, as a result of variation of the heat transfer coefficient of the ammonia. These two figures together allow us to determine the variation in the design area of the heat exchanger as a result of variation in the transport properties of the ammonia. As an example of the use of these diagrams we take the situation when the viscosity of the ammonia exceeds the reference value by 10%

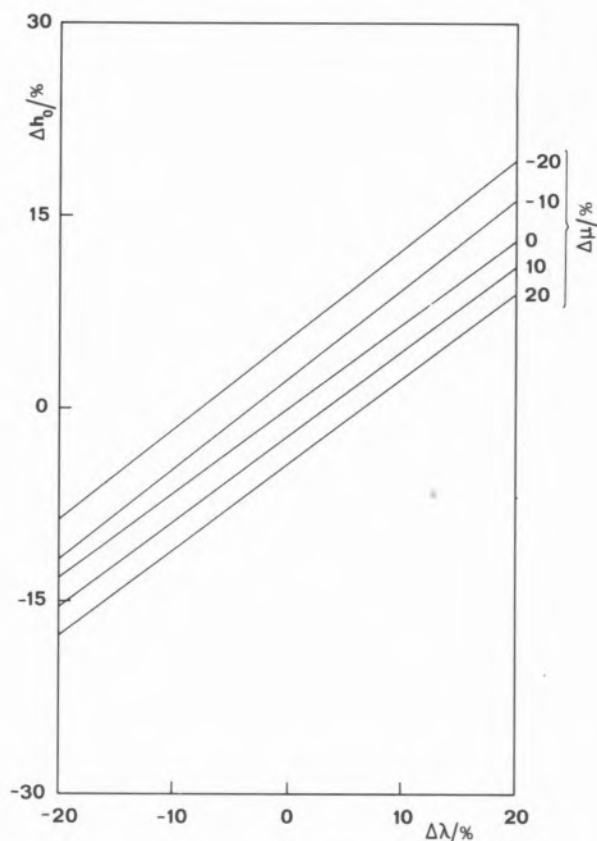


Fig. 1

The influence of the fluid transport coefficients upon the outside film heat transfer coefficient, for the heat exchanger.

$$\Delta h_o = \frac{(h_o)_c - (h_o)_r}{(h_o)_r} \times 100\%$$

$$\Delta \mu = \left(\frac{\mu - \mu_r}{\mu_r} \right) \times 100\%$$

$$\Delta \lambda = \left(\frac{\lambda - \lambda_r}{\lambda_r} \right) \times 100\%$$

The subscript r denotes reference conditions

and the thermal conductivity is 15% below its reference value. Then it follows from fig. 1 that Δh_o is about -15% and from fig. 2 that ΔA_o is +14%. Thus as a result of these errors in the transport coefficients alone, the heat exchanger area is overestimated by some 14%. The results for the condenser are qualitatively the same with a variation in the area of -14% to +26%, as can be seen from fig. 3 and 4.

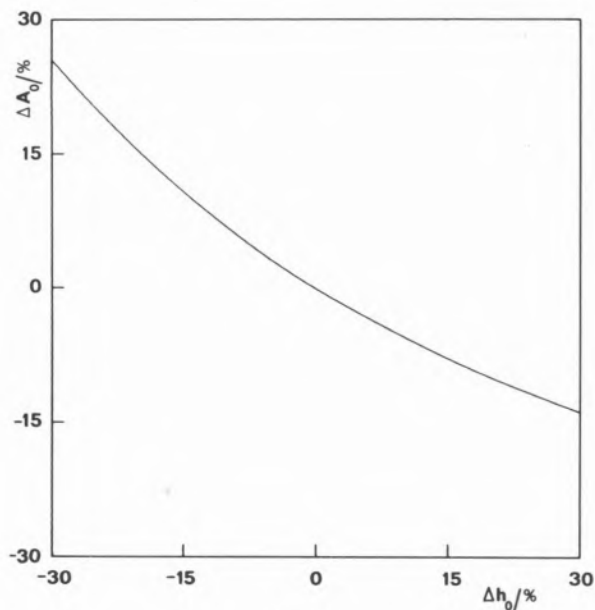


Fig. 2

The influence of the outside film heat transfer coefficient upon the heat transfer area for the heat exchanger

$$A_o = \left\{ \frac{A - (A_o)_r}{(A_o)_r} \right\} \times 100\%$$

The remainder of the legend is the same as for fig. 1

In an earlier paper [1] it was shown that for many fluids or fluid mixtures it is at present impossible to estimate their transport properties to within $\pm 20\%$. Here we have shown that because of such uncertainties alone it is possible to over- or under- estimate the heat transfer area for a heat exchanger or a condenser to fulfil a particular need by as much as 25%. Of course it must also be recognised that any methodology for heat exchanger design such as that given here has an inherent uncertainty by virtue of its empirical nature. Generally, this latter uncertainty is accommodated into a practical design by increasing the design heat transfer area by a multiplicative safety factor. The results of our calculations might therefore be interpreted as a demonstration that the safety factor should be increased to allow for the effect of uncertainty in the fluid transport properties. For example, if in the condenser we evaluate a hypothetical fouling factor R' , which represents the effective additional resistance to fluid property uncertainties, we obtain values that range

from -0.003 to $+0.001$. Such values are comparable with the value of R employed in the reference design. If this argument is pursued then merely because of $\Delta\lambda$ and $\Delta\mu$ heat exchangers or condensers may be manufactured 25% larger than necessary at a typical incremental cost of some 23%. Although this increase represents a small fraction of the total capital expenditure on a particular chemical plant the total extra expenditure, taken over a series of plants and a number of years, represents a considerable extra expenditure. It must be stressed that these increased costs are in addition to, and not a part of, the costs incurred by faults in design procedures.

An alternative interpretation of the results of our calculations is, however, possible. If the uncertainties in the estimation of the transport coefficients of fluids could be reduced to a few percent from their present high values, then the over-design of heat exchange equipment could be similarly reduced. Such a reduction could be

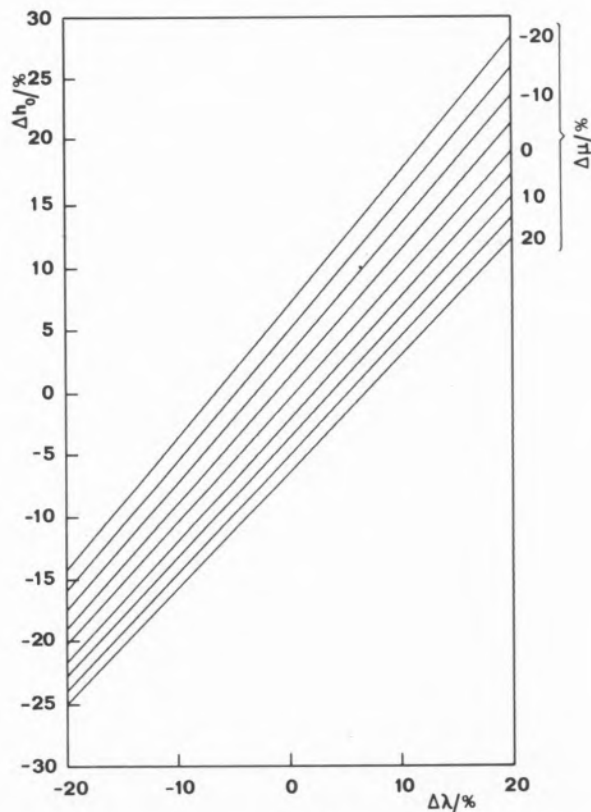


Fig. 3

The influence of the fluid mixture transport coefficients upon the outside film heat transfer coefficient, for the condenser

The legend is the same as for fig. 1

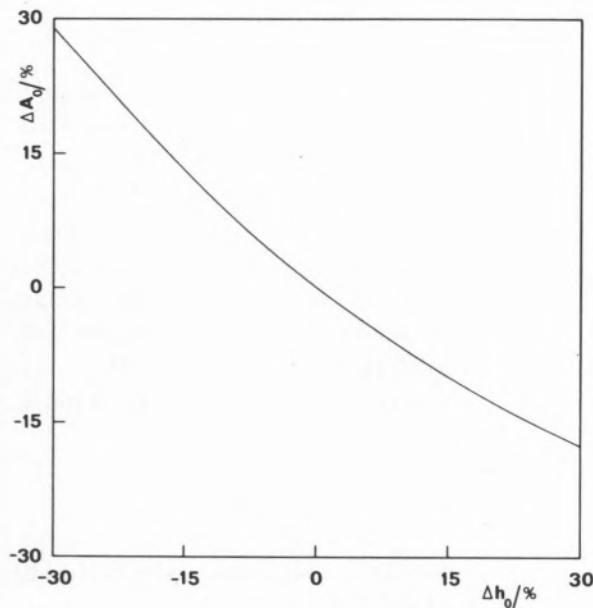


Fig. 4

The influence of the outside film heat transfer coefficient upon the heat transfer area for the condenser
The legend is the same as for fig. 2

achieved by a series of accurate measurements on carefully chosen systems, supported by the development of fundamental theories and subsequently estimation schemes. The incremental costs of only three items of plant equipment (about 40,000 US dollars) would provide a significant contribution to such a research effort with the corresponding savings rapidly justifying the initial expenditure.

In summary, research effort in the field of the transport properties of fluids has been shown to

have a quantitatively important technical and economic role in the optimum design of at least some items of chemical process plant.

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RESUMO

Analisa-se a influência que a utilização de técnicas de estimativa normalmente utilizadas em engenharia química têm no projecto e operação de unidade de transferência de calor presentes em instalações químicas correntes.

Utilizam-se como exemplos um permutador de calor e um condensador. Mostra-se que as incertezas nos coeficientes de transporte resultantes de métodos correntes de estimativa de propriedades têm um efeito significativo no projecto tecnológico global do equipamento de transferência de calor, contribuindo para um aumento de gastos de capital.

Demonstra-se ser possível reduzir estes gastos adicionais pelo desenvolvimento de métodos de estimativa mais correctos, baseados em dados experimentais das propriedades de transporte de fluidos com maior exactidão.