A NOVEL FOULING CELL TO STUDY INFLUENCE OF SOLUTION ON CRYSTALLISATION FOULING

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ABSTRACT

A novel fouling cell has been developed to assess the effect of process solution chemistry on crystallisation fouling. This device consists of a jacketed vessel with two heated vertical copper fingers suspended in the solution from above. The substrates are heated by a recirculating flow of liquid and operate under conditions of constant temperature driving force. The fouling cell was designed to emphasise simplicity yet still allow the key surface material and coating chemistry effects to be captured. The thermal performance of the fouling cell was characterised using thermochromic liquid crystals.

The cell was used to study crystallisation fouling from aqueous solutions containing calcium carbonate. One advantage of the device is that when identical test sections are used, separate destructive analytical techniques can be used to determine the composition and microstructure of the fouling layer(s). The results are compared with those obtained from a simple co-current heat exchanger operating under forced flow conditions. Good agreement in deposit structure and composition was found.

The rate of fouling was monitored from heat transfer measurements and from changes in solution composition. Mass balances confirmed that the change in solution chemistry matched the growth in deposit. Kinetic analyses indicated that deposition was controlled by mass transfer to the surface.

INTRODUCTION

Heat exchanger fouling is the build-up of unwanted material on heat transfer surfaces, and the deleterious effects of fouling on heat transfer are well documented for many industrial and domestic systems. Often it is not practicable to use real heat exchangers from industry or from domestic devices to study characteristics of a fouling process. Reasons for this include, but are not necessarily limited to; expense (some heat exchanger configurations can have complex geometries and are therefore expensive to produce), time (on some systems it can take an unreasonably long time to deposit sufficient fouling material for an effective study) and practicality (heat exchangers can be parts of very complicated systems and decommissioning and/or recommissioning can be technically challenging, time consuming and expensive). Therefore, it is convenient to build laboratory analogues for real heat exchanger systems in order to reproduce the characteristics of a fouling system to be studied. This paper presents details of the design and development, as well preliminary experiment results for, a test cell designed to study the influence of solution chemistry on the prevalence of crystallisation fouling.

Crystallisation fouling is one of the five principal fouling mechanisms identified by Epstein (1983). It occurs in heat exchangers when the concentration of a solute exceeds its solubility limit at the heat transfer surface. This paper focuses on inverse solubility solutions (containing solutes whose solubility decreases with increasing temperature - often termed 'retrograde' behaviour) and heated surfaces. The surface provides pathways for heterogeneous nucleation and a crystalline deposit may nucleate and grow there. Examples of inverse solubility salts include calcium carbonate, calcium sulphate and magnesium silicate (Bott, 1995; Brooke, 1984). Inverse solubility salts can also participate in particulate fouling, when precipitation of crystalline material in the bulk solution leads to deposition at the heat transfer surface (see Hawthorn and Wilson, this conference). Crystallisation fouling can also arise with normal solubility salts when the solution is subject to evaporation and on cooled surfaces. The test cell presented here is similar in concept to the 'cold finger' devices used to study wax deposition (Jennings and Weispfennig, 2005).

In heating, ventilation and air conditioning (HVAC) systems, the deposition of calcium carbonate and other hardness salts can be problematic since these systems are designed to run for long periods of time with little maintenance. Water softening units can be used but would require continual renewal. The composition of the feed water is largely determined by the geology of the installation location. It is useful to know the susceptibility of a device or system to fouling, and the composition of the feed water is a key determining factor. Certain waters may preclude the sale of an HVAC device in an area or necessitate re-engineering of a system to counteract fouling (Kawaley, 2015). It is therefore important to use a systematic approach to study the effect of solution composition on fouling. This paper reports results from an ongoing study of hard water scaling on copper surfaces.

We present a fouling rig which has several desirable and unusual features that aid the study of the effect of solution composition on fouling. Firstly, the design of the apparatus emphasises simplicity and most of the parts are standard fittings. The test cell shares similarities with the heated probe system employed by Geddert *et al.* (2011), where electrically heated test strips were suspended in a reservoir of the solution of interest. Their unit operated under constant heat flux while our device employs constant temperature driving force. The solution of interest only contacts the heat transfer surfaces and the glass walls of the reservoir. This means that fouling upstream of the test section, which can occur in more complex apparatuses, cannot occur. Furthermore, the system is easy to clean between experiments.

The apparatus features two identical test sections. This allows separate, destructive analyses to be undertaken using deposit generated from a single batch of process solution. In this study, one sample was subject to quantitative compositional analysis using inductively coupled mass spectrometry (ICP-MS) and the second was used for microstructure and composition analysis by scanning electron microscopy (SEM) and related methods.

The deposit is formed on the external surface of a vertical cylindrical annulus. Surface temperature is a key parameter and the clean heat transfer performance of the test cell was characterised using thermochromic liquid crystals (TLCs). TLCs change in colour at a particular temperature and are used in medical devices, thermometers and novelty mugs. The colour change and transition temperature is determined by the liquid crystal material. The temperature transition width for the TLCs used here was 0.1 K. Their use in heat transfer studies, for determining local heat transfer coefficients, is well established in aerospace applications (Ireland & Jones, 2000, Manzhao *et al.* 2008) where the heated fluid is usually air.

The use of TLCs to study liquid phase heat transfer is much less common because most TLCs are not very stable in water. This was mitigated in this study by the use of microencapsulated TLCs. The ability to determine the local surface temperature, and thus estimate the local heat transfer coefficient, was particularly important given the complex and non-standard fluid flow configuration in the fouling cell reservoir: extensive computational fluid mechanics simulations similar to those reported by Huang *et al.* (2012) would otherwise have been required.

EXPERIMENTAL METHODS

Design and optimisation of fouling rig

Figure 1 shows schematics and photographs of the fouling rig. A 5 litre, 150 mm inner diameter cylindrical jacketed glass vessel serves as the reservoir. The charge of liquid in the reservoir was stirred by a 70 mm magnetic stirrer bar rotating at 150 rpm. Its temperature was maintained by circulation of water from a heater/chiller unit through the jacket. The glass walls allow the solution to be monitored for precipitation; insulation can be applied if needed.

The Reynolds number at the tip of the stirrer is approximately 22 000 (at a bulk temperature of roughly 50° C). The stirring speed was set at the fastest rate that the stirrer could be operated stably. The purpose of the stirrer bar

was primarily to ensure that the fluid in the vessel was well mixed and there little variation in temperature in the bulk liquid. Separate studies (not reported here) established a weak dependency of h_0 on stirrer speed.

The system contains two test devices which are mounted in the reservoir lid on a diameter, equidistant from the centre. The test device consists of a flow connection (Figure 2(c)) and a test section (Figure 2(a)). These studies used copper test sections 160 mm long, wall thickness 0.65 mm, fabricated from standard 15 mm o.d. domestic copper piping (alloy C12200). In these experiments the bottom 120 mm of the finger is in contact with the process solution when the rig is assembled. This sets the area for heat transfer.



(b)



Figure 1. Fouling cell: (a) schematic; (b) photograph.

The bottom end of each test section was sealed by crimping closed a 5 mm length using a vice, with a small amount of glue located inside the crimped region to ensure that the section remained watertight. The crimped design proved superior to soldering a cap on to the end of the tube as crimping maintained uniform surface chemistry. Tests with a soldered cap gave preferential nucleation at the joint, caused by the tin and other metals present in the solder alloy.

The heating water is pumped from the circulator through a flow control valve and rotameter before entering the flow connection through the top of the fitting. It flows down to the bottom of the finger along a vertical 140 mm long \times 6.5 mm o.d. \times 0.75 mm wall thickness brass tube collinear with the unit axis. The water then flows up the annular gap between up the tube and text section. A helical guide, fabricated from a 25 cm length of 1 mm thick aluminium wire, was wrapped around the inner tube to ensure that the hot water did flow evenly up the annular gap. The effectiveness of the guide was confirmed by the TLC testing, which did not show any bias in the surface temperature distribution which would result from channelling. For the fouling tests reported in this work, the hot water flow solution flow rate was 1.2 litre/min and the inlet temperature was 80°C, corresponding to a Reynolds number in the annular gap of 1900.



Figure 2. Photographs of test device components: (*a*) clean test section - note crimped end at bottom; (*b*) fouled section; (*c*) flow connection, with helical insert fitted.

The heating water passed through the two devices in series. T-type thermocouples measured the hot water temperature at the inlet and outlet of the fingers. The temperature drop across the device was used to calculate the amount of heat transferred and the average heat flux. Another T-type thermocouple located some distance away from the heated surfaces the temperature of the bulk solution.

The fluid flow pattern around the test sections was not modelled as this would require computationally expensive computational fluid dynamics calculations to be carried out. (see Huang *et al.*, 2012) The TLC measurements provided an indication of flow similarity.

Heat transfer measurements

The average heat flux was used in combination with TLC measurements of surface temperature to estimate the external film heat transfer coefficient, h_0 . The coatings used (R38C1W, LCR Hallmark) changed colour from black to blue at 39.7°C (Figure 3).

The temperature at which the TLCs changed colour was confirmed by heating the substrate as described above but with air as the external fluid, using infrared thermography to confirm the surface temperature, T_s (FLIR One infrared camera). This calibration had to be performed in air as the curvature of the vessel and the infrared absorbance of the water in the reservoir meant that infrared thermography was unsuitable for measuring T_s when the fouling cell was in its normal configuration. The fact that infrared thermography was unsuitable for T_s measurement during a fouling experiment provides further justification for using TLCs to estimate h_o .

For heat transfer tests the apparatus was set up as for a fouling test but with reverse osmosis (RO) water in place of the fouling solution. Test sections were coated with TLC by the supplier: the coating thickness was measured by digital callipers as 10 μ m. The temperature of the water in the reservoir was maintained at 30°C. Keeping the flow rate of heating water constant, the temperature of the heating water was increased in steps by increments of 0.5 K, starting at 40°C, until the TLC colour change occurred. Care was taken to ensure that the system reached steady state between each step. Figure 3(*b*) shows a relatively uniform colour transition.



Figure 3. Photographs showing colour change of thermochromic liquid crystal coated fingers: (*a*) $T_s < 39.7^{\circ}$ C; (*b*) $T_s = 39.7^{\circ}$ C. The second, uncoated test section is evident on the right of each image.

Fouling tests

Calcium carbonate hardness is defined here in terms of the concentration of dissolved calcium. The solutions used in the tests reported here contained 100 mg/l or 200 mg/l Ca. The solutions were prepared by mixing CaCl₂.6H₂O (Fisher Scientific) and NaHCO₃ (Fisher Scientific) in RO water. The solutions were shaken thoroughly and allowed to rest to ensure that all components had sufficient time to dissolve. The pH of the solutions was measured regularly and ranged from 7.5 – 8.0. Aliquots were withdrawn from the reservoir periodically to track the change in composition: the experiments were run in batch mode and the salt concentrations were not topped up during a test.

Analysis of solution and deposits

Much of the analysis was performed using facilities at the department of Earth Sciences, University of Cambridge. The concentration of calcium in solution was determined by ICP-MS. The material deposited on the copper substrate was dissolved off the substrate using 2M HCl before analysis with ICP-MS. These data were used to confirm via a simple mass balance that the material leaving solution was depositing on the copper finger. Table 1 presents examples of the mass balance: the agreement is considered good.

Table 1: Mass balances for fouling tests in Figure 6 and 7(b)

Initial [Ca] (mg/l)	[Ca] after 40 h (mg/l)	Change in mass in solution (mg)	Mass of deposit on fingers (mg)
200	88 ±7	560±35	557 ±20
100	65 ±7	175±35	163 ±20

Scanning electron microscopy (SEM) on the fouling material indicated the shape, size and packing of the deposited crystallites. Some images were taken of the deposit surface while in others, the finger was mounted in resin and cross sectioned. Images were taken using an FEI Quanta SEM. The samples were analysed for elemental composition and mapped using energy dispersive x-ray spectroscopy (EDS) using a Bruker Quantax EDS probe. Some crystallographic identification was undertaken using powder diffraction (using a Bruker D8 Advance Diffractometer), while some crystallographic identification was attempted using electron backscatter diffraction (EBSD) using a Bruker Quantax EBSD probe in the SEM. To the authors' knowledge this paper presents the first example of use of EBSD for crystallographic identification of fouling deposits.

RESULTS AND DISCUSSION

Characterisation of heat transfer

TLC-coated fingers were used to estimate the thermal performance of the clean system. From Newton's law of cooling, the heat flux between the copper surface and the bulk process solution, $q_{\text{conv,o}}$, is proportional to the temperature difference between the surface, T_{s} , and bulk solution, T_{b} :

$$q_{\rm conv,o} = h_{\rm o} \left(T_{\rm s} - T_{\rm b} \right) \tag{1}$$

The product of the overall heat transfer coefficient, U, and area for heat transfer, A, is given by

$$1/UA = 1/h_{i}A_{i} + R_{c} + R_{w} + 1/h_{o}A_{o}$$
[2]

where *h* is a heat transfer coefficient and subscripts *i* and *o* are inside and outside, respectively. The conductive resistances for the coating and wall, $R_c + R_w$, are can be calculated using

$$R_{\rm c} + R_{\rm w} = \ln(r_{\rm o}/r_{\rm i})/2\pi k_{\rm w} + \ln(r_{\rm o} + \delta_{\rm c}/r_{\rm o})/2\pi k_{\rm c}$$
[3]

Here *r* is a radius, *k* thermal conductivity ($k_w \approx 400 \text{ W/m K}$ for copper, $k_c \approx 0.2 \text{ W/m K}$) and δ_c the coating thickness. Eqn. [3] gave the conductive resistances to be 0.14 m K/kW. The rate of heat transfer, *Q*, from the heating fluid through the

finger and into the bulk solution is estimated from the change in heating water temperature, via:

$$Q = \dot{m} C_p \left(T_{\text{inlet}} - T_{\text{outlet}} \right)$$
[4]

where \dot{m} is the mass flow rate, C_p is the specific heat capacity of water and T_{inlet} - T_{outlet} is the temperature drop across the finger. UA is then calculated from the heat exchanger design equation,

$$Q = UA \ \Delta T_{\rm LM} \tag{5}$$

where $\Delta T_{\rm LM}$ is the log mean temperature difference:

$$\Delta T_{\rm LM} = (T_{\rm inlet} - T_{\rm outlet}) / \ln((T_{\rm inlet} - T_{\rm b}) / (T_{\rm outlet} - T_{\rm b}))$$
[6]

The TLC coating allows h_0 to be determined explicitly, allowing h_i to be calculated from Eqn. [2]. The three heat transfer coefficients, U, h_i and h_0 , are plotted against the Reynolds number in the annular region for the flow rates relevant to the fouling tests in Figure 4.



Figure 4. Effect of heating water flow rate on heat transfer coefficients (*a*) without helical insert, (*b*) with helical insert. Symbols: U – solid squares; h_0 – open circles; h_i – solid circles.

Figure 4 shows that h_0 is consistently smaller than h_i ; this result, coupled to the difference in heat transfer area ($A_0 > A_i$), means that U is therefore more sensitive to external convection effects. Parameters such as the stirring rate of the bulk solution therefore need to be kept constant between experiments in order to achieve reproducible results.

Figure 4(*b*) also shows that the helical insert increases h_i , as a result of reducing channelling. There is little impact on *U*, but the more uniform flow pattern gives a more uniform surface temperature distribution and hence deposition: Figure 2(*b*) shows a relatively uniform fouling layer on the test section.

The data in Figure 4 are presented in Figure 5 in terms of the Nusselt number, Nu (the ratio of convective to conductive heat transfer), calculated thus:

$$Nu = h d / k$$
^[7]

where *d* is the characteristic length, either the hydraulic diameter of the annular channel (for h_i in Nu_i : also used to calculate Re) or the outer diameter of the test section (for h_o in Nu_o)

The data for Nu_i can be compared with results in the literature for annular geometries. Dirker and Meyer (2005) provide a good summary of empirical relationships to predict heat transfer through annular pipes. The Dittus-Boelter correlation for well-developed turbulent flow in a smooth pipe is

$$Nu = 0.\ 023\ Re^{0.8}\ Pr^{0.4}$$
[8]

where Pr is the Prandtl number. For annuli, correlations include the McAdams correlation (1954)

$$Nu = 0.031a^{0.15}(a-1)^{0.2}Re^{0.8}Pr^{1/3}(\mu/\mu_{\rm w})^{0.14}$$
[9]

and the Foust and Christian correlation (1940)

$$Nu = (0.04a/(a+1)^2) Re^{0.8} Pr^{0.4}$$
[10]

Here, *a* is ratio of the external and internal surface areas. Nu_i increases with Re, as expected. The magnitude of Nu_i is > 60, indicating that heat transfer is in the laminar regime. Inspection of Figure 5(*b*) indicates that the trend follows the $Re^{0.8}$ dependency in Eqns. 8 to 10 but the magnitude of Nu_i is greater than that predicted by the correlations, both with and without the helical ribbon present. The Foust and Christian result gives the closest agreement, but it is still approximately 100% smaller. One of the reasons for this is that the Reynolds number is lower than the lower limit of the range usually quoted for these correlations, so the result is very sensitive to roughness effects. This was not explored further.

Calcium carbonate fouling

Figure 6 shows a typical plot of U against t for a 40 h long fouling experiment in the rig. The data are also plotted in the form of the fouling Biot number, $Bi_{\rm f}$, which quantifies the extent of fouling:

$$Bi_{\rm f} = U_{\rm clean} R_{\rm f}$$
^[11]

where U_{clean} is the value when clean, and R_{f} is the thermal resistance due to fouling, given by:

$$R_{\rm f} = 1/U - 1/U_{\rm clean}$$
 [12]



Figure 5. Effect of heating water flow rate, expressed as annulus Reynolds number, on Nusselt number (*a*) with helical insert; (*b*) without insert. Symbols as in Figure 4: $Nu_{overall}$ – solid squares; Nu_i - filled circles; Nu_o - open circles. Loci show predictions for comparison with Nu_i : solid line – Dittus-Boelter, Eqn. [8]; dashed line – McAdams, Eqn. [9]; dotted line - Foust and Christian, Eqn. [10];

Figure 6 shows that $Bi_{\rm f}$ is small throughout the duration of the experiment (< 0.1), indicating the temperature of the deposit surface does not change appreciably from the clean substrate over the course of the experiment: *U* changes by less than 5%. $Bi_{\rm f}$ (and $R_{\rm f}$), which quantifies the effect that fouling has on heat transfer, increases almost linearly after a short induction period of 2-4 h and reaches an asymptote at $Bi_{\rm f} \approx 0.06$ after roughly 25 hours.

The approach to a fouling asymptote matches the chemical composition results in Figure 7. The latter plot shows that the calcium concentration in the bulk solution decreases, with nearly three quarters of the total amount of material to be deposited leaving solution within the first 25 hours or so of the experiment.

The horizontal line on Figure 7 shows the saturation concentration of calcium, C_{sat} , at the surface temperature of the copper finger, T_{s} , for $T_{\text{s}} = 63^{\circ}$ C. C_{sat} was calculated by solving the set of coupled equilibria described by Plummer and Busenburg (1982) for the deposition of calcium carbonate using a MATLAB script. With sufficient time, the concentration of calcium in solution approaches this line asymptotically, as shown in Figure 7(*a*).



Figure 6. Evolution of thermal performance of a copper surface, presented in terms of U (black symbols) and Bi_f (red symbols).Test conditions; 200 mg/l Ca; heating liquid flow rate = 1.2 l/min; inlet temperature $\approx 80^{\circ}$ C, bulk liquid temperature = 46°C; $T_s \approx 63^{\circ}$ C. The spike in Bi_f at 36 h is an artefact.

The data in Fig. 7 give a good fit to an integrated first order kinetic model of the type:

$$\ln\left(\Gamma\right) = -k_{\rm m,\,eff}\,t + \ln\left(\Gamma\right)_{t=0}\tag{13}$$

where Γ is the concentration driving force for deposition, calculated by subtracting the saturation concentration, C_{sat} , at a given point in time from the measured bulk concentration, C_{bulk} . The gradient of a logarithmic plot yields $k_{\text{m,eff}}$, the effective mass transfer coefficient. The two plots in Figure 7 are for different initial starting concentrations. Fitting Eqn. [13] to the data sets yielded similar values of $k_{\text{m,eff}}$, as presented in Table 2. The magnitude of these mass transfer coefficients is close to that expected from the measured value of h_0 via the heat and mass transfer analogy.

Table 2: Comparison of $k_{m, eff}$ and $k_{r, eff}$ for data sets in Figure 7, calculated using Equations (13) and (14), respectively.

Initial [Ca] (mg/l)	$k_{ m m,eff}$ (1/s)	<i>k</i> _{r, eff} (1 /mol s)
100	0.000012	0.032
200	0.000011	0.0059

Also shown in Table 2 are the values of the second order reaction constant, $k_{r, eff}$, calculated assuming kinetic control,

when the reaction is deemed to be second order in calcium and carbonate ion (taken to be related to calcium concentration (Hasson and Zahavi, 1960):

$$1/\Gamma = 1/\Gamma_{t=0} + k_{r, eff} t$$
 [14]

Table 2 confirms that the external mass transfer mechanism controls deposition in these cases as $k_{r,eff}$ varies with initial concentration. The rate of deposition is limited by mass transfer from the bulk solution and the surface of the copper substrate, in a similar fashion to the overall heat transfer coefficient being limited by transfer from the copper substrate to the bulk solution.



Figure 7. Evolution of calcium concentration in reservoir for test with same experimental conditions as Fig. 6. Solid symbols – [Ca]; open symbols – Γ . Horizontal solid line indicates [Ca]_{sat} for the surface temperature in this test. (*b*) Test with 100 mg/l Ca. Dotted line in both cases shows fit of data to Equation [13].

The amount of inorganic carbon in solution was also measured. The CO_3^{2-} concentration could be estimated from these measurements using the system of equilibria for calcium carbonate described by Plummer and Busenburg (1982). The concentration of CO_3^{2-} at the start of the tests was approximately 5×10^{-5} mol/l, which is considerably less than the starting Ca^{2+} level (5×10^{-3} mol/l). The concentration of CO_3^{2-} was largely invariant over time, indicating that CO_3^{2-} is replenished by deprotonation of HCO_3^{-} ions (an instantaneous process). The system was not perfectly isolated from the atmosphere, which meant that CO_2 could be absorbed from the atmosphere, which accounts for the modest change in pH observed (from around 8.0 to 7.5).

Microstructural analysis

Scraping some of the deposit off the substrate and examining it with powder diffraction suggested that the predominant depositing phase was aragonite. This is consistent with other studies of heterogeneous nucleation of calcium carbonate at elevated temperature (*e.g.* Besevic *et al.* 2017; Noda *et al.* 2013; Tai and Chen, 1998). An SEM micrograph of the deposit is shown in Figure 8; the characteristic needle shaped structure of aragonite is apparent (Tai and Chen, 1998; Hu and Deng, 2004).



Figure 8. SEM micrograph taken using secondary electron mode of sample described in Figure 6.

Figure 9 shows an EBSD map of a small region near the surface of the copper. The sharp transition between copper and aragonite is consistent with SEMs of the cross-section. This corroborated the powder diffraction data, and provides a tempting glance at the possibilities of using EBSD for structural mapping of crystalline fouling material.

Comparison with conventional fouling rig

Besevic *et al.* (2017, this conference) present results for similar series of experiments, using a co-current lab heat exchanger. In both cases, the rate of deposition appeared to be limited by mass transfer and aragonite was the principal phase which deposited.



Figure 9. EBSD map of cross-section of sample obtained from fouling run in Figure 6.

The values of the film mass transfer coefficient, k_m , for each device are now compared. k_m can be estimated from the value of $k_{m,eff}$ via

$$k_{\rm m} = k_{\rm m,eff} \, ({\rm V/A}) \tag{15}$$

where V is the volume of the solution. The values are reported in Table 3 alongside the film heat transfer coefficients. Both the heat and mass transport coefficients are larger in the cocurrent cell, as expected: the tests featured a Reynolds number in the duct of 4 400. From the heat and mass transfer analogy, one would expect the ratio of mass transfer coefficients to be similar to the ratio of the heat transfer coefficients, and this is the case (0.37 vs. 0.39). This result indicates that similar deposition mechanisms are involved. It should be noted that this comparison is facilitated by the use of the TLCs to estimate the h_0 values directly.

Table 3: Comparison of mass and heat transfer coefficients for the test cell described in this paper and the co-current heat exchanger fouling rig described in Besevic *et al.* (2017).

$k_{ m m}$	$k_{ m m}$	$h_{ m o}$	$h_{ m s}$
finger test cell	co-current test cell	finger test cell	co-current test cell
(m/s)	(m/s)	(W/m^2K)	(W/m^2K)
4.8×10 ⁻⁶	1.2×10 ⁻⁵	3450	9430
$k_{ m m},_{ m finger}$ / $k_{ m m},_{ m co-current}$ -		$h_{ m o}/h_{ m s,}$ -	
0.39		0.37	

The apparatus described in this paper is significantly easier to clean and to set up between experiments. Taking aliquots for kinetic data and scraping deposited material off the copper fingers for diffraction studies are both straightforward.

A fouling cell of this design has general applicability. The substrates can readily be fabricated from other metals, including coated surfaces. The bulk solution can be varied, so long as it is not too viscous. Investigations at different temperatures could be achieved by using alternative heating fluids.

Difficulties associated with the test cell described in this paper include the curved surfaces of the vessel, which can make it hard to detect and image the substrate as fouling occurs. The curved surface of the test section means that as more material deposits, the radius of the fouling finger increases and the surface area of the substrate also increases: it follows that that the heat transfer performance is less sensitive to deposition of additional fouling material as the deposited layer gets thicker. Furthermore, the curved surface of the test section can make it difficult to measure the thickness or the roughness of the fouling layer.

CONCLUSIONS

A new fouling test unit has been design, commissioned and used to study crystallisation fouling caused by calcium carbonate solutions. It was designed for supporting experiments using different process solutions. Its thermal characteristics were measured using thermocouples and TLCs: these established that heating was controlled by external heat transfer factors.

A unique feature of the fouling rig is the use of identical test sections, one for compositional analysis, and the other for structural analysis. Calcium carbonate deposition in this fouling rig was found to be mass transfer limited. The depositing phase, verified by XRD, SEM and EBSD, was predominantly aragonite. This was consistent with data collected from fouling studies using a more conventional co-current heat exchanger.

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NOMENCLATURE

Roman

a	Ratio of internal and external diameter for annulus, -
Α	Heat transfer area, m ²
$Bi_{\rm f}$	Biot number for fouling, -
$C_{ m bulk}$	Bulk concentration, mol/m ³
$C_{\rm p}$	Specific heat capacity, J/kg K
$C_{\rm sat}$	Saturation concentration, mol/ m ³
h	Heat transfer coefficient, W/m ² K
k	Thermal conductivity, W/m K
$k_{\rm m,eff}$	Effective mass transfer coefficient, 1/s
$k_{ m r, eff}$	Effective reaction coefficient, 1 / mol s
'n	Mass flow rate, kg/s
Pr	Prandtl number, -
Q	Heat transfer rate, W
q	Heat flux, W/m ²
R	Thermal resistance, m ² / W K
$R_{ m f}$	Thermal resistance due to fouling, m ² K/W
Re	Reynolds number, -
r	Radius. m

t Time, s

- T Temperature, °C
- U Overall heat transfer coefficient, W/m²K
- V Volume of solution, m³

Greek

- δ Thickness of layer, m
- Γ Concentration driving force, mol/m³
- λ Thermal conductivity, W/m K

Subscripts

с	Coating
clean	Clean
f	Fouling layer
i	Inside
inlet	Inlet
0	Outside
outlet	Outlet
S	Surface

S Surface

w Wall

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