FIELD-FOULING UNITS FOR REFINERY EXPERIMENTS*

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ABSTRACT

Two skid mounted field test units were designed and installed at two refineries for fouling data. Each fouling test unit contains test sections with a heat transfer monitor, an onboard computer for acquiring data, controls and instruments, and piping networks for start-up, sampling, and shut-down procedures. Both units are designed according to ASTM specifications for service in refinery or chemical plants. One fouling test unit is designed for two-phase flow of hydrogen and the product stream, the second for single-phase flow of crude oil, which has two heat transfer monitors operating independently. Calculation procedures for the heat transfer coefficient and fouling resistance are presented along with heat transfer data for air and water obtained at Argonne National Laboratory and crude oil obtained at the Shell Wood River refinery. Comparisons are made with the theoretical heat transfer coefficients.

INTRODUCTION

A major question in fouling research is how to relate experimental data obtained in the laboratory using batch test equipment to "real" fouling in once-through processes in the field. Batch systems, which are common in laboratory experiments, provide useful data; however, it is difficult to develop a credible method for applying the data to once-through operations. Compositional changes due to the consumption and production of the key fouling species, as well as the bulk compositional changes due to maintaining the fluid at elevated temperatures, must be included in the model. Furthermore, due to the complex nature of petroleum fluids, it is difficult to develop a generic method.

Researchers at Argonne National Laboratories (ANL) developed two field test units, as a first step towards (1) understanding the mechanisms of crude and product stream fouling on industrial heat exchangers, (2) evaluating fouling mitigation techniques, and (3) developing a scale-up methodology. The first unit was designed for installation at the Chevron El Segundo refinery in California. This unit was designed to obtain information on the mitigation of fouling in the two-phase flow of hydrogen and product stream such as heavy gas oil and jet fuel. The second field fouling unit, which was installed at the Shell Wood River refinery in Illinois, was designed for single phase fouling experiments of crude oil. Both units receive test fluids from split streams supplying the fluid to heat exchangers. The fluid is then returned back to the process stream at a suitable location so that the needed pressure drop is available for covering a wide range of flow rates.

DESIGN OF THE FIELD UNITS

Simplified flow diagrams of the two-phase and single-phase test units are shown in Figures 1 and 2, respectively. Photographic views of the two are shown in Figures 3 and 4, respectively. The photographs illustrate their overall layout and scale. The units are self-contained, skid-mounted, test rigs with all the controls and data-acquisition instruments necessary to create and monitor fouling, and explore various options for fouling mitigation. Some mitigation options include chemical additions, variations in heat flux and flow rates, enhanced tubes, and tube inserts. Both units were designed to run continuously, and collect data with minimal effort from the operators at the refineries.

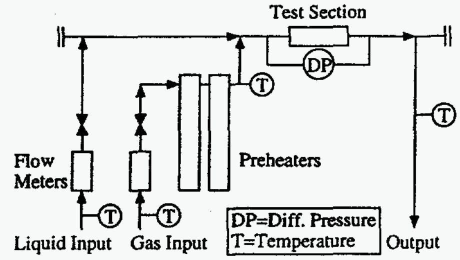

Figure 1: Flow Diagram for the Two-Phase Unit

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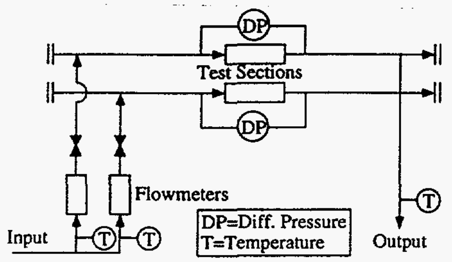

Figure 2: Flow Diagram for the Single-Phase Unit

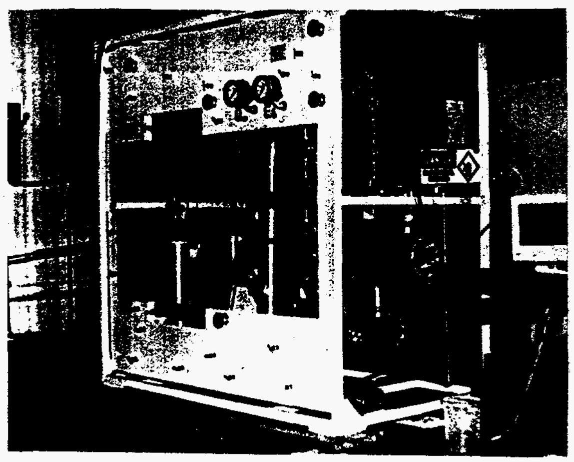

Figure 3: Photograph of the Two-Phase Unit

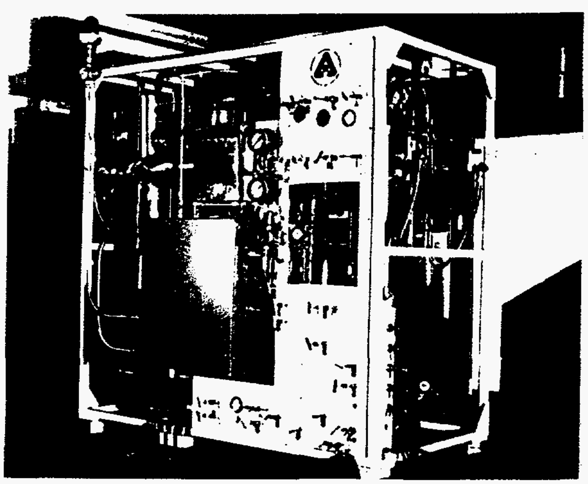

Figure 4: Photograph of the Single-Phase Unit

The major design features and specifications of the two fouling units are summarized in Table 1. In general, the two units were designed using similar parts and components, which include: the test section, data-acquisition system, instrument piping system, drain header, and power supplies for the heat transfer monitors. Each test section contains the following: a heat transfer monitor (HTM), a differential pressure cell across the fouling region, a flow meter, and a control valve. A computer data-acquisition system, power supplies, and short-haul modems are all contained within a NEMA 4 computer box mounted on the skid. The piping network is designed for starting and stopping the unit, purging, venting, sampling liquids, draining, and pressurizing the system. Inlet and outlet valves are equipped with a block and bleed arrangements for isolating the unit from the process system.

Table 1. Design Specifications for Field Fouling Units.

	Two-Phase	One-Phase
HTMs		
Material	321 SS	410 SS
Tube ID	0.0152 m	0.0211 m
Tube OD	0.0334 m	0.0254 m
Block Material	carbon steel	carbon steel
Block Diameter	0.102 m	0.102 m
Heating Length	0.229 m	0.226 m
Heating Capacity	5.0 kW	5.0 kW
Instruments		
Flow Meters	Venturi meter	Vortex shedding
Thermocouples	K Type	K Type
Total Thermocouples	17	41
Pressure Transducers	Strain gauge	Strain gauge
Diff. Pressure Cells	Strain gauge	Strain gauge
Control Valves	Kammer	Kammer
Operating Parameters		
Fluid	Hydrocarbon and Hydrogen	Crude Oil
Flow Rates:	0.5 - 1.5 m/s	1.2 - 2.3 m/s
Liquid	0.5 - 2.8	N/A
Gas	m^3/min	
Temperature	400 °C	200 - 425 °C
Pressure	20.7 X10^6 Pa (3000psi)	3.45 X10^6 Pa (500 psi)
DAS		
Computer	Pentium 166	Pentium 100
Software	LabTech Control	LabTech Control

In the two-phase unit, the process fluid and hydrogen are supplied separately and mixed in a special design of a T-section with gas injected in the center of the pipe section thereby ensuring establishment of two-phase flow in a short distance. Generally, hydrogen is supplied at a lower temperature than the process fluid; therefore, a preheater is installed to heat hydrogen to the temperature of the mixed flow. In the single-phase unit, the key feature is the installation of two test sections. With this design option, we can obtain fouling data on the two test section simultaneously with the same feed, but with different test conditions. This is an important feature because the bulk fluid temperature, and even crude quality, can change during a given test period. In that case, one of the two sections can be used as a control or reference and the effectiveness of mitigation methods and determination of threshold conditions can be directly evaluated. Also, enhancements, such as wire inserts or ribbed tubes, may be used in one test section while the other test section runs as a benchmark.

Data Acquisition System

The onboard personal-computer (PC) system acquires data from the unit, and sends control signals to the heaters and control valves. There are seventeen thermocouples in the two-phase unit and forty-one thermocouples in the single-phase unit. In general, there are twelve thermocouples in each HTM: one thermocouple is located upstream and one downstream of each HTM, one thermocouple is welded on each band heater for overtemperture cut-offs, and two thermocouples read temperatures of the bulk fluid at the entrance and exit of each test section. Each unit also collects data from differential pressure cells to measure pressure drops across the HTMs and flow-rate readings from venturi and vortex flowmeters. Inputs to the fouling test units from the computer include signals to both the heaters and flow control valves. These correspond to heat rates of 0 to 5000 Watts on the HTMs, 0 to 22,000 Watts on the hydrogen preheater, and positions of 0 to 100% open on the control valves. A PID (proportional, integral, and differential) control is built into the computer software. The PID control is only applied to the flow control valves. A feedback loop is used between the flow meters, the computer, and the control valves.

Heat Transfer Monitor

A photographic view of the HTM is shown in Figure 5, and a cross-sectional diagram is shown in Figure 6. The HTM in each test section consists of an assembly of heating blocks installed on the pipe by a shrink-fit method that provides a good thermal contact between the test section and the heating block. Four sets of three thermocouples are installed in each block; two sets of thermocouples at each of the inlet and outlet ends of the heated section. Each set of thermocouples provides temperature gradient data for block. From this data, the heat flux and wall temperature at the fluid/wall interface are calculated. By measuring the temperature gradients at inlet and outlet, an average value for the heat transfer coefficient for the whole test section is calculated. The fouling resistance at time t is calculated by taking a difference of the reciprocal of the heat transfer coefficient at time t and that at t = 0 when the probe surface is in the clean condition. High heat flux is created by 480 volt band heaters fastened tightly around the heating block. The heating block for the single-phase unit is 9 inches long and has a diameter of 4 inches. The band heaters were procured from Watlow Electric Company. Two band heaters are used for each HTM. These heaters are capable of providing heat fluxes of about 333 kW/m^2 at the inner surface for the single-phase unit (460 kW/m^2 for the two-phase unit), and temperatures up to 500 °C at the outside of the block. An external thermocouple is welded on the outside of each band heater to act as an overtemperature cut-off. As shown in Figure 6, three thermocouples are secured within the block at distances of 1.34, 3.12, and 4.71 centimeters from the centerline.

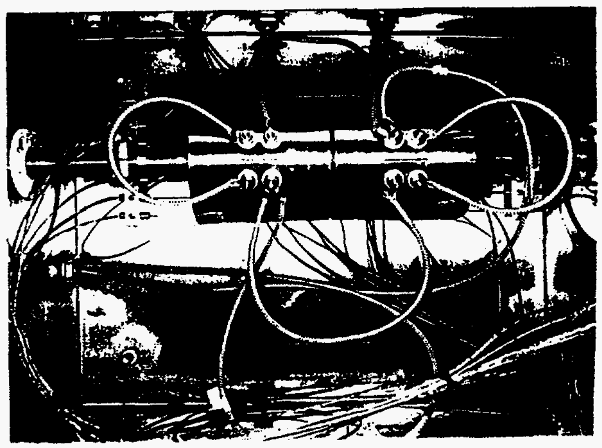

Figure 5: Photograph of the HTM

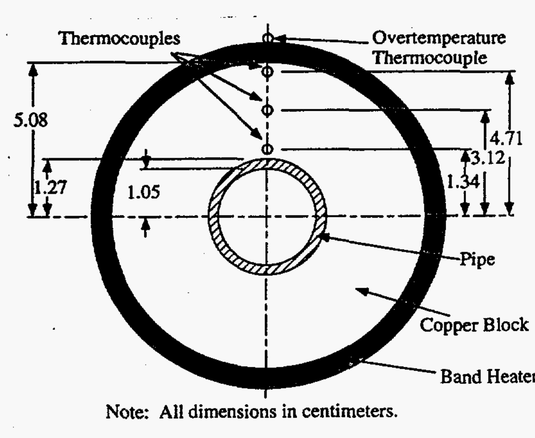

Figure 6: Cross-section of the HTM

Calculation Procedures

Temperature readings from the thermocouples mounted in each of the heat transfer monitors are used to calculate the heat flux and temperature profiles within the heating block. A diagram of the HTM and the locations of the thermocouples are shown in Figure 6, and an example of the temperature profile obtain within a HTM is shown in Figure 7. Calculations proceed by first calculating averages for the temperatures in each HTM block. Each radial location (3 total) in the block is calculated as an average of four temperatures. Next, the slope (S) and intercept (I) of a straight line between a plot of the local temperature versus the log of position is calculated. From these values, the temperature at the pipe-block interface, T_I, is calculated by

$$T_I = S \ln(r_I) + I \quad (1)$$

Also, from the slope of this curve we can calculate the heat rate by

$$Q = (\pi\, d_I\, L)\, k_{block}\, S / r_I \quad (2)$$

The thermal conductivity of the block, k_{block}, is calculated at the log mean average of the block temperatures. The surface temperature, T_S, and the heat transfer coefficient are then calculated by

$$T_S = T_I - Q \ln(d_I/d_S) / (2\, \pi\, k_{pipe}\, L) \quad (3)$$

$$h_{exp} = Q / (L\, d_S\, \pi\, (T_S - T_{fluid})) \quad (4)$$

Finally, the fouling resistance at different times is calculated by

$$R_f = (1/h)_{t=t} - (1/h)_{t=0}\ , \quad (5)$$

where h at t = 0 is an average of the heat transfer coefficient during the clean surface condition.

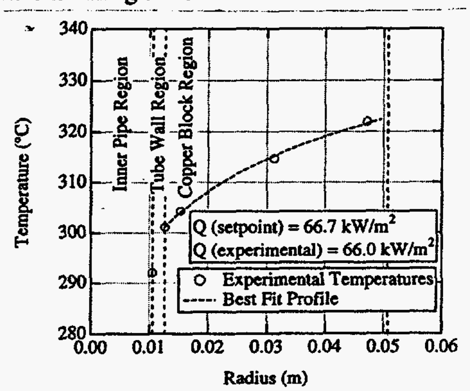

Figure 7: Predicted HTM temperature profile and experimental values

HEAT TRANSFER MEASUREMENTS

Functionality tests of the HTMs, control valves, computer system, and other instruments of the field fouling unit were performed at ANL. Heat transfer and flow-calibration tests were performed using water in the single-phase unit and water and air in the two-phase unit. Also, a series of heat transfer measurements were taken at the Shell refinery with crude oil before starting the fouling experiments. The two-phase unit is not yet installed; therefore, the heat transfer data with the process fluid are not available.

The flow calibration results for the two types of flow meters are shown in Table 2. The estimated measurement accuracy of the venturi meter is about 1.5%. The accuracy of the Vortex meter is close to the manufacturer's value of 1.5% at the meter, but is greater as read by the computer. The results show that the flow rate measurements are within the estimated accuracy of flow meters.

Table 2. Flow Calibration Tests.

Flow meter Reading kg/hr	Measured Flow Rate* kg/hr		Difference %	
Two-Phase Unit (Venturi Meter)				
500	499		0.3	
1000	983		1.7	
1500	1485		1.0	
2000	1950		2.5	
Measured Flow Rate L/min	Meter L/min	Diff., %	Computer L/min	Diff., %
One-Phase Unit, HTM#1 (Vortex Meter)				
45.20	44.97	0.5	45.73	1.2
21.54	21.35	0.9	21.08	2.2
32.10	31.65	1.4	32.10	0
45.96	45.73	0.5	45.99	0.1
HTM#2 (Vortex Meter)				
44.33	43.72	1.4	40.81	8.6
17.91	17.60	1.7	17.22	4.0
30.36	30.28	0.3	27.56	9.2

* Measured flow by collecting water and weighing it.

The purpose of conducting heat transfer tests was to determine the measurement accuracy of the HTMs. Table 3 provides a summary of the tests conducted at ANL using water and air for the two-phase unit. The measured pressure drops for water were within about 10% of the predicted values; however, the error for air tests was greater than that for water. The pressure drop for two-phase flow could not be measured for all tests due to the instrument set limits; however, the measured pressure drop for two tests was in reasonable agreement with the predicted values.

Table 3: Heat Transfer Results for the Two-Phase Unit.

Test	Flow Rate kg/hr Water	Flow Rate kg/hr Air	Pressure Drop kPa Test	Pressure Drop kPa Predict	Heat Transfer Coefficient kW/m² K Test	Heat Transfer Coefficient kW/m² K Predict
1	0.253		1.38	1.44	5.85	6.33
2	0.189		0.78	0.85	5.55	5.11
3	0.127		0.39	0.44	3.94	3.80
4	0.200		1.24	1.44	5.63	6.92
5	0.190		0.78	0.85	4.87	5.59
6	0.126		0.39	0.43	3.69	3.79
7		0.0076	0.92	1.05	0.19	0.13
8		0.0091	1.11	1.50	0.19	0.15
9		0.0038	0.46	0.32	0.13	0.08
10		0.0076	0.98	1.05	0.13	0.13
11	0.037	0.0081	5.23	4.58	5.32	4.52
12	0.082	0.0081	Pegged	6.67	8.05	7.57
13	0.126	0.0081	Pegged	8.44	9.46	8.96
14	0.076	0.0038	4.12	2.62	5.20	5.56
15	0.126	0.0038	Pegged	3.86	7.01	7.57

The experimental heat transfer coefficient for water is within 10% of predicted values; however, the heat transfer values for air are greater than the experimental results on an average by 30%. The HTMs are designed to measure high values of heat transfer coefficients for liquid and two-phase flows; therefore, it is not surprising that the measurement accuracy for air is relatively low. The measurement accuracy for two-phase flow is within 10% of the predicted value. Because the fouling resistance is measured as a change in the heat transfer coefficient, the measurement accuracy for the rate of fouling will be better than 10%. These results clearly demonstrate the measurement accuracy of the HTM in the field fouling unit.

The single-phase unit was also tested with water at ANL, but the number of tests were limited because of the shipping schedule to the refinery. However, the results showed that the measurement accuracy was similar to that for the two-phase unit. After the installation of the unit at the refinery, a series of heat transfer tests were conducted. A summary of these results is presented in Table 4. The major conclusions from the heat transfer tests are as follows:

- the measured heat transfer coefficient is 20–30% greater than that predicted by the Petukhov-Popov [1] correlation for heat transfer,
- heat transfer coefficients tend to agree better at lower liquid flow rates,
- measurements from the two HTMs are consistent, and
- measurements are reproducible.

The major uncertainty in predicting the heat-transfer coefficient may be in estimating the physical properties of crude oil. Crude-oil properties were obtained from Perry [2]. The refinery heat transfer results demonstrated that the field unit should generate fouling data within an acceptable accuracy level.

Table 4: Heat Transfer Results for Crude Oil.

Test #	Test hrs	HTM	V m/s	Temp. °C fluid	Temp. °C wall	Heat Flux kW/m² Test	Heat Flux kW/m² Calc.	Heat Transfer Coefficient kW/m² K Test	Heat Transfer Coefficient kW/m² K Predict
1	24	1	1.52	216	226	20	19.2	2.20	1.81
		2	1.49		223	20	14.8	2.56	1.78
2	24	1	1.52	217	226	20	19.3	2.24	1.82
		2	1.49		223	20	16.6	2.54	1.78
3	24	1	0.87	233	244	20	18.3	1.49	1.32
		2	2.73		237	20	16.0	4.89	3.46
4	24	1	2.78	233	239	20	18.9	4.29	3.58
		2	0.89		242	20	15.6	1.53	1.35
5	72	1	1.51	227	236	20	18.7	2.30	2.02
		2	1.49		234	20	15.2	1.93	1.99
6	1	1	1.15	230	263	50	49.5	1.61	1.64
		2	0.94		255	43	36.4	1.35	1.38

FOULING WITH THE SINGLE PHASE UNIT

Fouling tests with the crude unit were started during the summer of 1996, after completing the heat transfer tests, as discussed above. A summary of the fouling tests performed to date is given in Table 5. The results show that fouling is negligible for the conditions of the first test (7/16/96 test). However, during the second test (8/2/96 test) the crude-oil inlet temperature increased by about 25 °C for a period of several days due to changing process conditions. This caused the wall temperature to rise by the same value for constant heat-flux conditions. Although the initial results should be considered preliminary, the fouling rates observed in the HTMs during this period were 0.011 and 0.026 (m^2 K/kW)/day (0.000062 and 0.00015 (hr °F ft^2/Btu)/day), respectively. The fouling rate for HTM#1 running at 1.16 m/s was lower than that for HTM#2 running at 0.98 m/s. After this test period, several start-ups and shut downs were necessary due to computer problems. Throughout this cycling process, the initial heat transfer coefficient for each test section had decreased indicating further deposition. Fouling tests were resumed, without cleaning the test sections, once the problems were resolved. Fouling curves for the last test series (12/19/96 test) are shown for both HTMs in Figure 8. During the first 320 hours of the test, HTM #1 had a fouling rate of 0.018 (m^2 K/kW)/day (0.0001 (hr °F ft^2/Btu)/day). The over temperature cut-off on HTM#2 tripped and was not restarted until after the Christmas Holidays. At that time, the power to both probes was increased to 93 kW/m^2. The apparent reduction in the fouling resistance at about 260 hours is due to an increase in the fluid heat transfer coefficient as the heat flux was increased. At 93 kW/m^2, fouling on both probes increased dramatically to 0.13 and 0.19 (m^2 K/kW)/day (0.00074 and 0.0011 (hr °F ft^2/Btu)/day), respectively. The effect of crude velocity on the rate of fouling was clearly identified in these results. The initial results seemed to indicate threshold wall temperatures in the range of 300 to 320°C for velocities below 1.2 m/s. This threshold wall temperature would be higher for velocities greater than 1.2 m/s. Moreover, the data suggest that initiation of fouling may occur during off-design conditions where the wall temperature increases and/or fluid velocity decreases for a short period of time, and it may progress at lower surface temperatures once the normal operating conditions are restored. Therefore, the heat exchange unit should be designed to tolerate such conditions and hence avoid the initiation of fouling.

Table 5. Summary of the Field Fouling Tests.

Start Date	Test hrs	HTM	Temp. °C Fluid	Temp. °C Wall	Heat Flux kW/m² Test	Heat Flux kW/m² Pred.	Heat Transfer Coefficient kW/m² K Test	Heat Transfer Coefficient kW/m² K Pred.	V m/s	Notes
7/16/96	408	1	230	260	50.0	50.0	1.50	1.64	1.15	No fouling
	408	2	230	255	43.3	36.7	1.30	1.39	0.95	No fouling
8/2/96	264	1	245	292	66.7	66.7	1.48	1.48	1.15	0.011 Rf/day*
	264	2	245	285	56.7	48.7	1.17	1.24	0.95	0.026 Rf/day
12/19/96	320 150	1	223	320 350	66.7 93.3	70.0 96.7	0.80 0.70	1.59	1.15	0.018 Rf/day 0.13 Rf/day
	320 150	2	223	325 350	66.7 93.3	56.0 85.3	0.60 0.60	1.38	0.97	Test Stopped 0.19 Rf/day

*R_f unit = m^2 K/kW

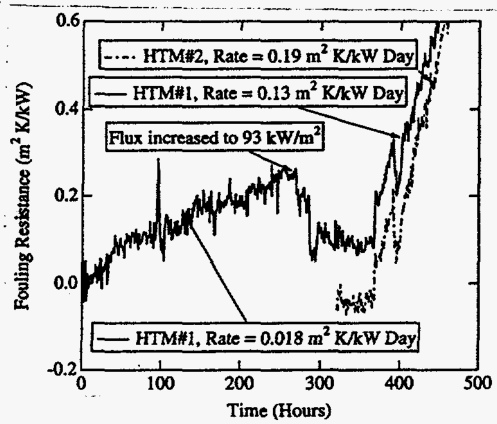

Figure 8: Fouling curves obtained with the single-phase unit at two different fluid velocities. HTM#1: V=1.15 m/s, HTM#2: V=0.97m/s.

CONCLUSIONS

Two field fouling test facilities are developed to investigate fouling mitigation techniques in refinery heat exchangers. The heat transfer results show that the units are capable of obtaining data with the required accuracy. Fouling curves for the single-phase test unit have given a clear indication of the effect of velocity and the supposition of threshold values. The overall benefit of the program will be to ascertain the effects of wall temperature and fluid velocity on threshold fouling conditions in an industrial setting.

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NOMENCLATURE

Cp	Heat capacity, kJ/kg K
d_i	Diameter at location i, m
D	Diameter, m
h	Heat-transfer coefficient, kW/m² K
I	Intercept
k	Thermal conductivity, kW/m K
L	Length of heated section, m
Pr	Prandtl number [= $C_p \mu / k$]
Q	Rate of heat transfer, kW
r_i	Radius at location i, m
Re	Reynolds number [= $D V \rho / \mu$]
R_f	Fouling resistance m² K/kW
T_i	Temperature at the copper/black pipe interface
S	Slope
t	Time, s or h
V	Velocity, m/s
ρ	Density, kg/m³
μ	Viscosity, kg/m s
μ_w	Viscosity at the wall, kg/m s

Subscripts

block	Copper block
exp	Experimental value
fluid	Fluid value
pipe	Pipe

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