To: Doctor Dahlke; Brewing Engineer Team

From: Nguyen Khoa Bui

Re: Characterization of heat exchanger for purchase

Dear Doctor Dahlke and Brewing Engineering Team,

A small-scale tube-and-shell heat exchanger was setup according to The Lab Manual to characterize heat transfer properties for various cold- and hot-side flowrates in co- and countercurrent flow (Heat Exchanger Experiment). For both flows, the overall heat transfer coefficient U is not impacted by change in hot-side flowrate but varied with change in cold-side flowrate. This may be due to hot-side flowrates were two to ten times larger than cold-side flowrates for many runs, which minimize the hot-side resistance impact on U. This make determining fouling effects not possible due to disagreement in constant c = 0.2 for countercurrent and infeasible value c = - 1.64 for co-current during parameters fitting. For both flow conditions, experimentally determined heat transfer coefficient h_i^{Exp} do not behave as expected when compared to that of Sieder-Tate correlation $h_i^{S\text{-}T}$. The data collected are considered accurate as all normalized Q_c+ Q_h are within the error propagation ranges. We concluded our data may only be used for countercurrent flow, limited to large hot-side to cold-side flowrate difference. We strongly recommend the brewing team to reconduct the experiment for a smaller flowrate difference between both sides and parameters should be re-fit.

Cc: Abdullah Alkazrai, Saeed Alharmoodi, Khalid Alsinan

Encl: 5 figures

Figures:

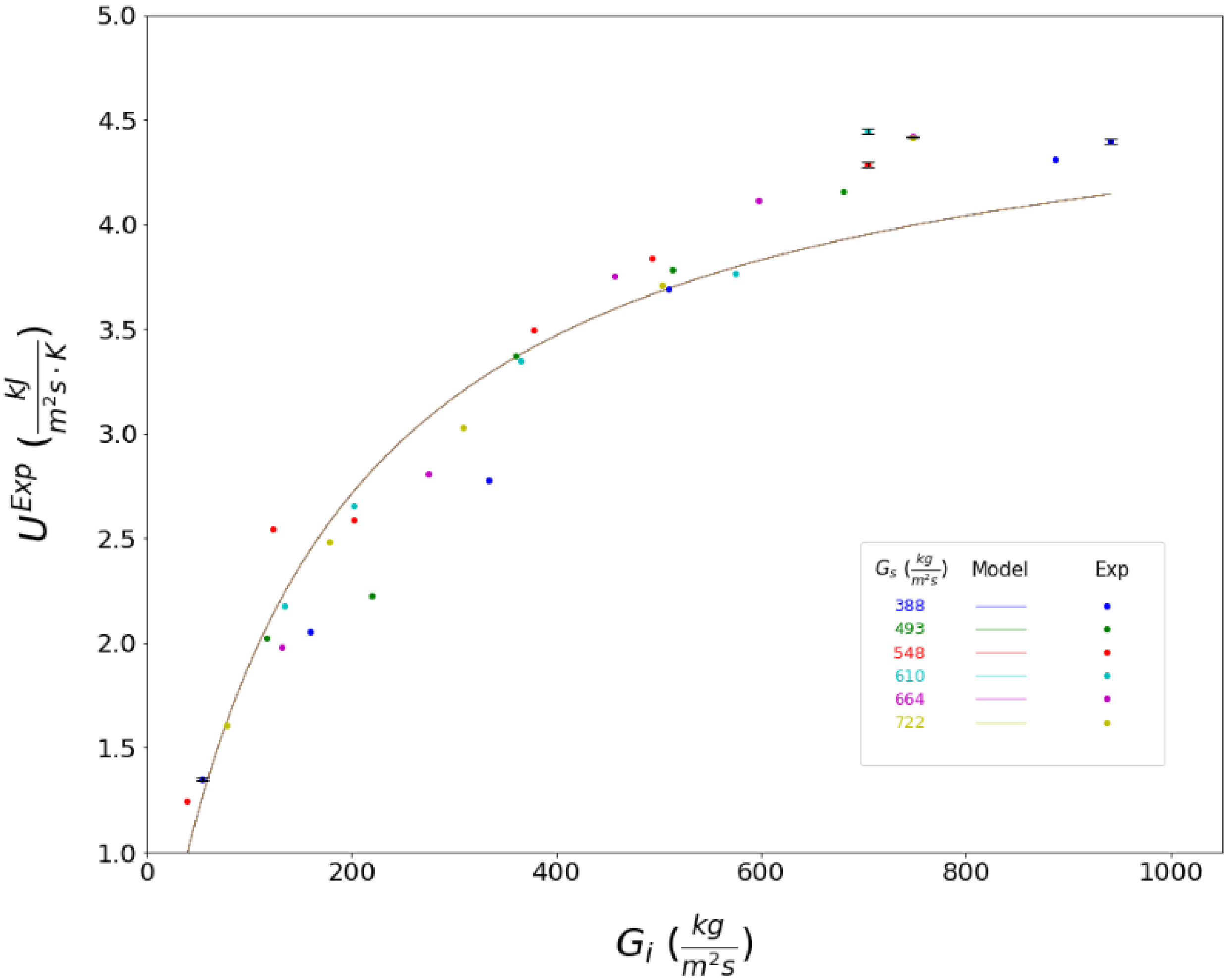

Figure 1. *plot of experimental and model overall heat transfer coefficient,* U_i^{Exp} *and* U_i^{Model} *versus mass velocity of tube-side* G_i *for various shell-side mass velocity* G_s *in countercurrent condition. Here,* $U_i^{model} = \frac{1}{\left(\frac{a}{G_i^b}+c+\frac{d}{G_i^e}\right)}$*, where* $a = 40.09\frac{s^{2.08}\cdot m^{4.16}\cdot K}{kJ\cdot kg^{1.08}}$*,* $b = 1.08$*,* $c = 0.23\frac{s\cdot m^2\cdot K}{kJ}$*,* $d = 0.44\frac{s^{6.93}\cdot m^{13.86}\cdot K}{kJ\cdot kg^{5.93}}$*,* $e = 5.93$*. While b value is close to Sieder-Tate expected value of b = 0.8, e value deviated greatly from Sieder-Tate value e = 0.55. These parameters result in all model trend for various* G_s *to clumped up into one line. Error bars for elements with repeated runs are presented and small compared to data point.*

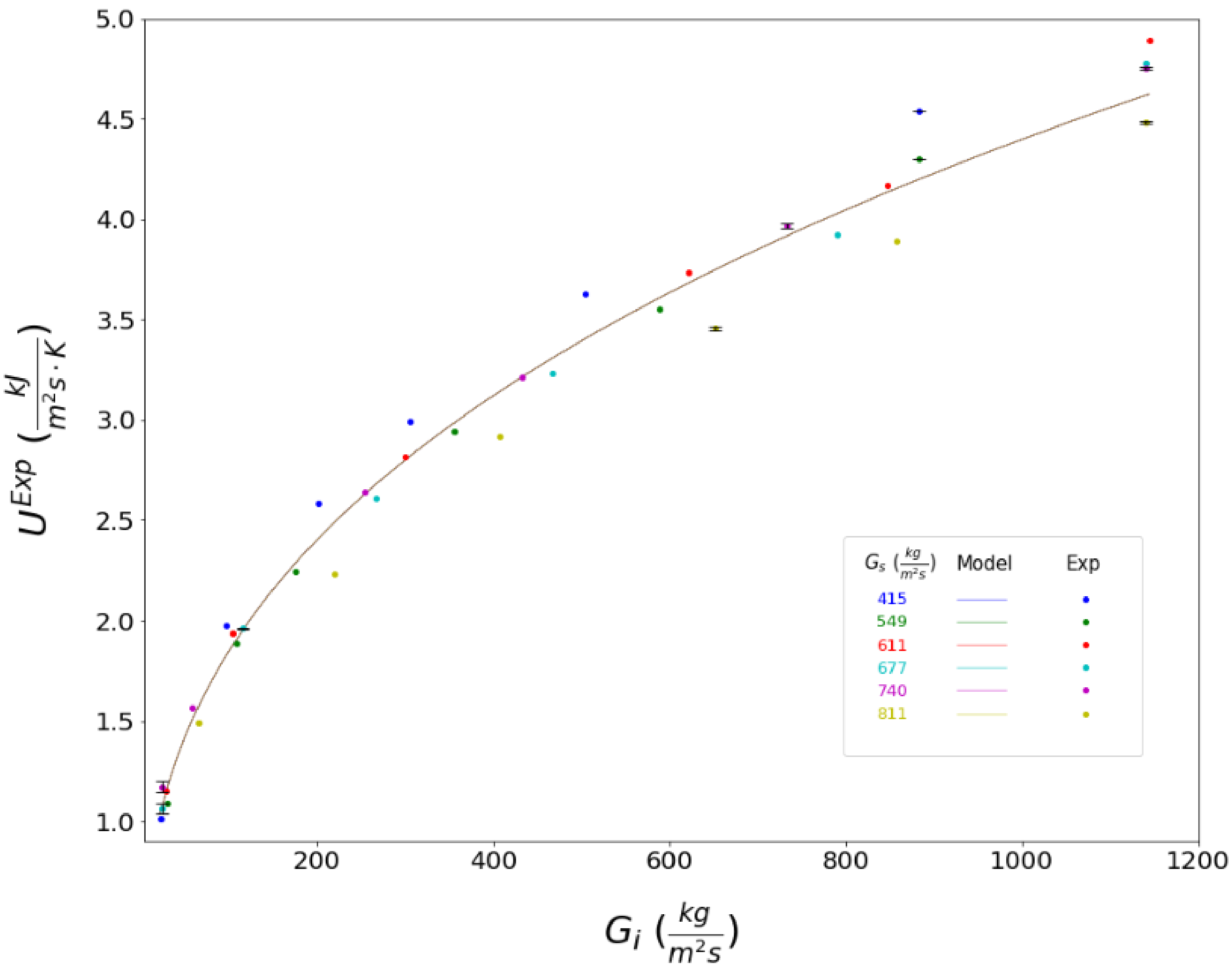

Figure 2. *plot of tube-side experimental U_i^{Exp} and model U_i^{Model} overall heat transfer coefficient versus mass velocity of tube-side G_i for various shell-side mass velocity G_s in co-current condition. Here, $U_i^{model} = \frac{1}{\left(\frac{a}{G_i^b}+c+\frac{d}{G_i^e}\right)}$, where $a = 2.68\frac{s^{1.31}\cdot m^{2.62}\cdot K}{kJ\cdot kg^{0.31}}, b = 0.31,\ c = -16.4\frac{s\cdot m^2\cdot K}{kJ}, d =\ 16.6\ \frac{s^{1.0}\cdot m^{2.0}\cdot K}{kJ\cdot kg^{2.62\times 10^{-3}}}, e =\ 2.62 \times 10^{-3}$. These parameters result in all model trend for various G_s to clumped up into one line. Both b and e values deviate greatly from expected values from Sieder-Tate where b = 0.8 and e = 0.55. Model yield negative value for c,* which is physically impossible despite proper fitting. Error bars for elements with repeated runs are presented and small compared to data point.

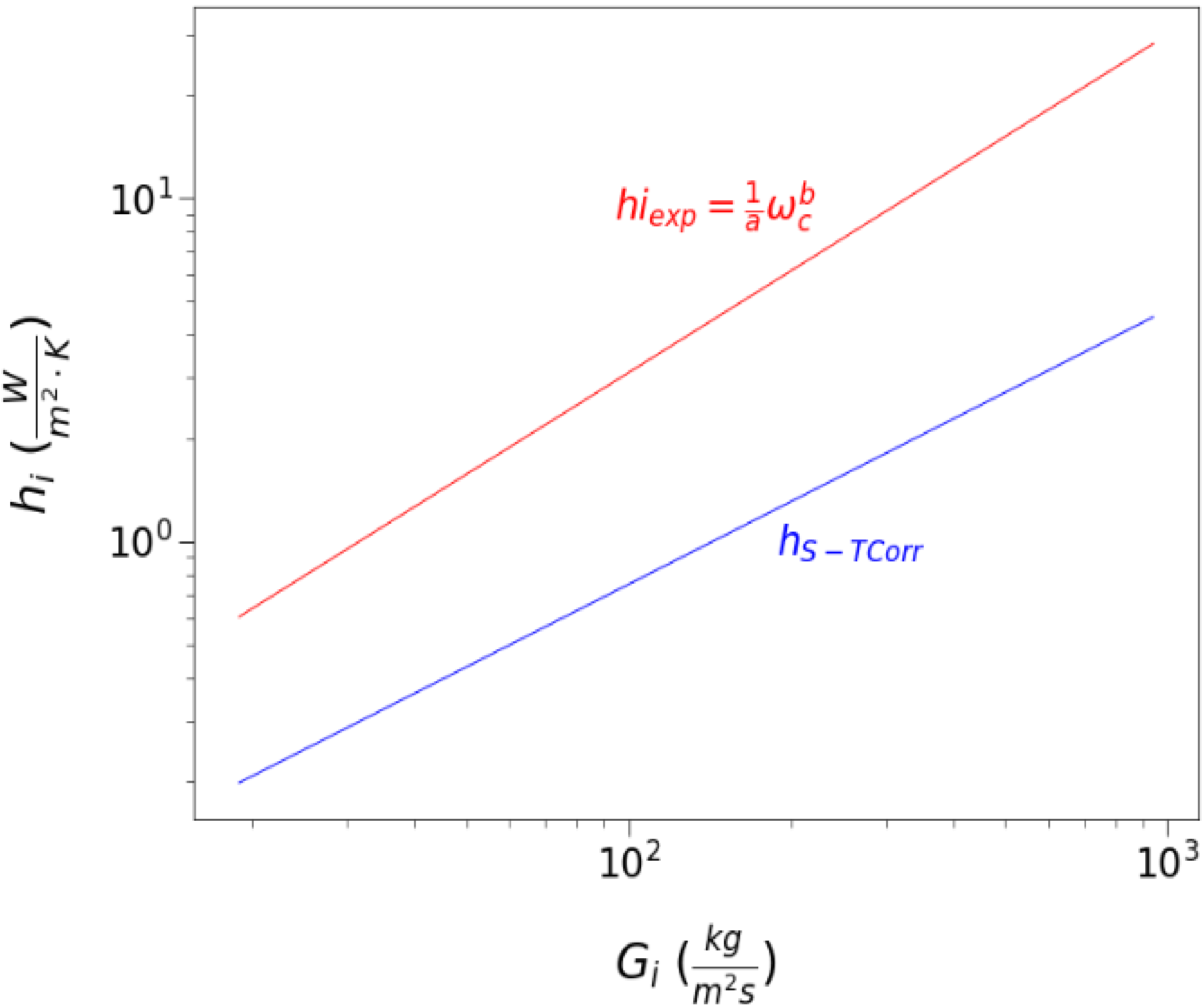

Figure 3. *log-log plot of tube-side experimental h_i^{Exp} and Sieder-Tate correlation $h_i^{S\text{-}T}$ heat transfer coefficient versus mass velocity G_i for countercurrent condition. Here, $h_i^{Exp} = \frac{1}{a}\omega_c^b$ where $b = 1.08$ and $a = 40.09\frac{s^{2.08} \cdot m^{4.16} \cdot K}{kJ \cdot kg^{1.08}}$. Both models portray the same trends on the log-log scale, but h_i^{Exp} values are four to ten magnitudes larger than $h_i^{S\text{-}T}$, scale inversely with G_i.*

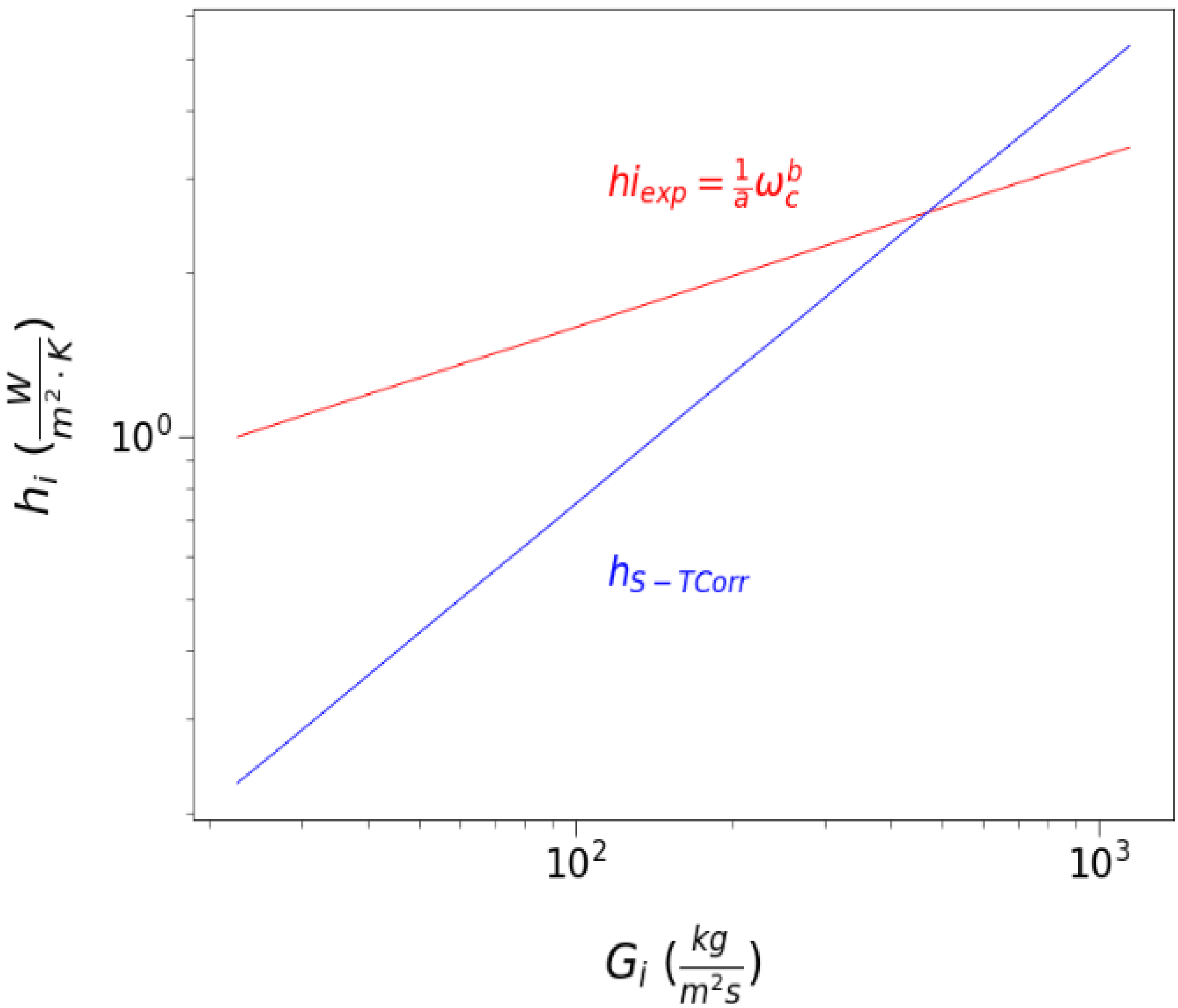

Figure 4. *log-log plot of tube-side experimental h_i^{Exp} and Sieder-Tate correlation $h_i^{S\text{-}T}$ heat transfer coefficient versus mass velocity G_i. for co-current condition. Here, $h_i^{Exp} = \frac{1}{a}\omega_c^b$ where $b = 0.31$ and $a = 2.68\frac{s^{1.31}\cdot m^{2.62}\cdot K}{kJ\cdot kg^{0.31}}$. h_i^{Exp} start off higher than $h_i^{S\text{-}T}$ at lower G_i but increase slower. This leads to an intersection point between the two model at $Gi = 420\frac{kg}{m^2 s}$.*

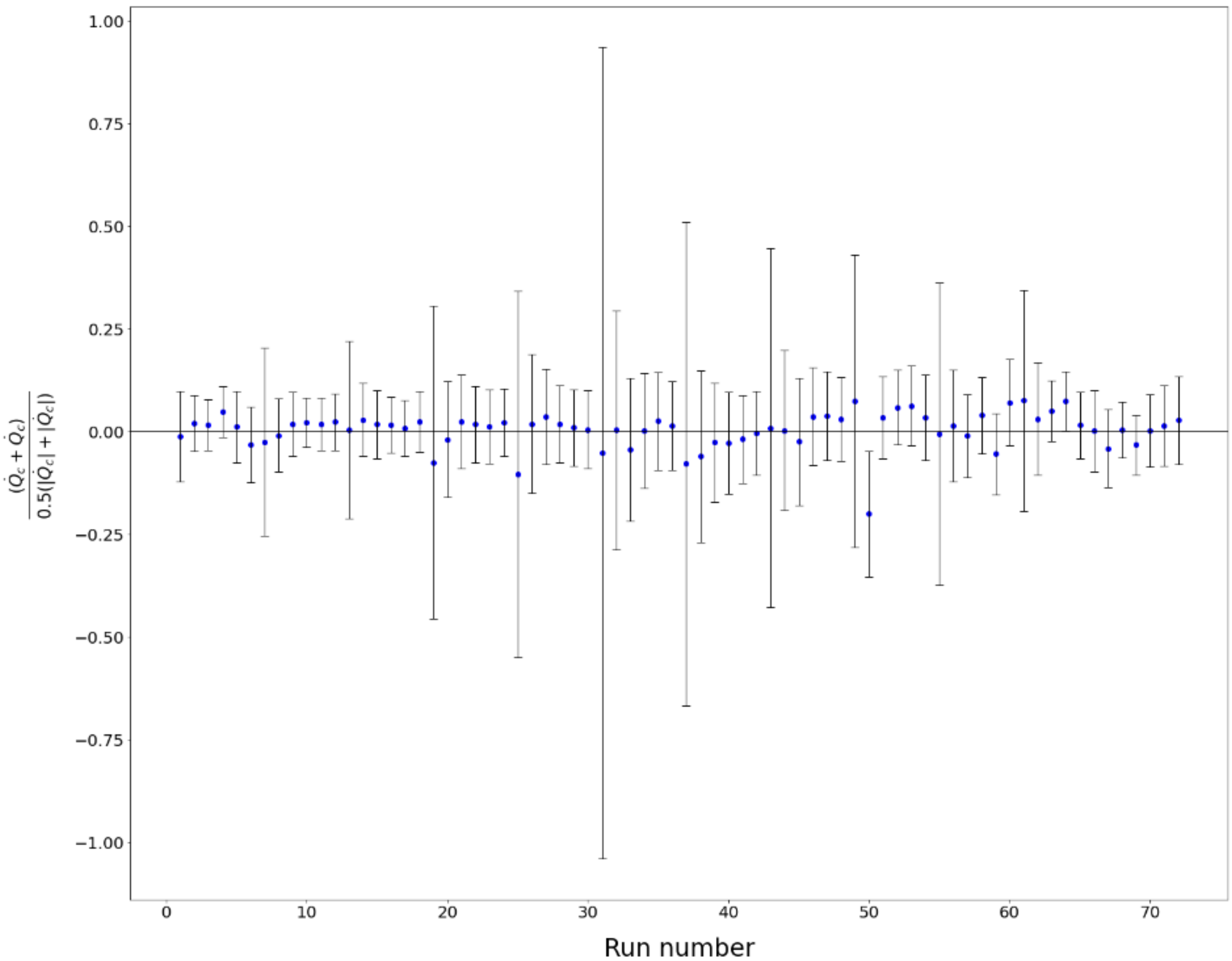

Figure 5. *Plot of normalized heat rate versus number of runs. All data point is within error tolerance with the normalized axis. Points deviations are noticed to be relatively small compared to error bars. Points with spiked error bars are of runs where G_i are around 10 times smaller than G_s. Errors are smallest for run with similar G_I to G_s. This shows that the data may be accurate, but is not precise, which is reflected through the unusual model fitting for co- and countercurrent.*

Appendix:

References:

(n.d.). *CBE 424 Lab Manual: Heat Exchanger Experiment.*

<u>Sample calculation:</u>

plot 1:

Fitting h_i^{model} Parameter: for countercurrent:

$$\frac{1}{U_{Exp}} = \frac{a}{G_i^b} + c + \frac{d}{G_s^e}$$

where: $U_{Exp} = \frac{Q}{A_i \, \Delta T_{LM}}$, $\Delta T_{LM} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)}$

$Q = \frac{|Q_c| + |Q_H|}{2}$, $Q_c = -Q_H$.

$Q_c = w_c \cdot C_p \cdot (T_{c,out} - T_{c,in})$ $\quad C_p = \cancel{4.188}\ 4.182\ \frac{kJ}{kg\,C}$

$Q_H = w_H \, C_p \, (T_{H,out} - T_{H,in})$

w_c and w_H is measured with bucket and stop watch: for 1 run.

$M_{c_1} = 1.5\ kg$, $t_1 = 40.1\ s$. $\Rightarrow$ $\boxed{w_{c_1} = 0.038\ \frac{kg}{s}}$

$M_{H_1} = 8.53\ kg$, $t_2 = 20.05\ s$ $\Rightarrow$ $\boxed{w_{h_1} = 0.42\ \frac{kg}{s}}$

$T_{c,out} = 38.66°C$, $T_{c,in} = 16.27°C$

$T_{h,out} = 53.69°C$, $T_{h,in} = 55.82°C$

$\cancel{T_{c,av}}$

$Q_{c_1} = 0.037 \left[\frac{kg}{s}\right] \cdot 4.182\ \frac{kJ}{kg°C}\ (38.7 - 16.3)°C = \boxed{3.5\ \frac{kJ}{s}}$ 3.

$\boxed{Q_{H_1} = -3.76\ \frac{kJ}{s}}$ (same calculation)

$\boxed{\text{T difference convert to Kelvin}}$

$$\boxed{Q_1 = \frac{|Q_c| + |Q_H|}{2} = 3.65\ \frac{kJ}{s}}$$

$N_T = 31$ (no. tubes)

$A_i = \pi D L \, N_T = \pi \cdot \left(0.821\,in \cdot \frac{in}{39.37\,m}\right) \cdot \left(7.875\,in \cdot \frac{in}{39.37\,m}\right) \cdot (31)$

$= 0.104\ m^2$.

$$\Delta T_{LM} = \frac{(\cancel{16.27}\ 55.82 - 38.66) - (53.69 - \cancel{55.82}\ 16.27)}{\ln\left(\frac{\cancel{16.27}\ 55.82 - 38.66}{53.69 - \cancel{55.82}\ 16.27}\right)} = \cancel{2.80}\ 26.0\ °K$$

$$\frac{Q}{A_i \, \Delta T_{LM}} = U_1 = 3.65 \left[\frac{kJ}{s}\right] \cdot \frac{1}{0.10\ m^2} \cdot \frac{1}{26\ K} = \boxed{1.35 \left[\frac{kJ}{m^2 K s}\right]}$$

accounted error:

$M_{c,2} = 7.52\,kg \quad , t = 40 \Rightarrow w_{c,2} = 0.038 \left[\frac{kg}{s}\right]$

$\text{Avg } w_{c} = \frac{w_{c,1} + w_{c,2}}{2} = \frac{0.037 + 0.038}{2} = 0.0377 \left[\frac{kg}{s}\right]$

$\text{std } w_c = \sqrt{\frac{(w_{c,Avg} - w_{c,1})^2 + (w_{c,Avg} + w_{c,2})^2}{2}} = \sqrt{\frac{(0.0377 - 0.37)^2 + (0.037 - 0.38)^2}{2}}$

$= 3.00 \cdot 10^{-4} \frac{kg}{s}$

$\boxed{w_c = 0.037 \pm 0.0003 \frac{kg}{s}}$

$\text{Avg } Q_{c,2} = \frac{Q_{c,1} + Q_{c,2}}{2} = 3.53 \left[\frac{kJ}{s}\right]$

$\text{std } Q_c = 0.0027 \left[\frac{kJ}{s}\right]$

$\Rightarrow Q_c = 3.53 \pm 0.0027 \frac{kJ}{s}$

$\boxed{Q = 3.65 \pm 0.0135 \frac{kJ}{s}}$

$\text{std } Q_c = \frac{|0.027| + |0|}{2} = 0.0135 \frac{kJ}{s}$

$\text{std } U = 0.0135 \frac{kJ}{s} \cdot \frac{1}{0.10\,m^2} \cdot \frac{1}{26K}$

$= 0.0049 \frac{kJ}{m^2 K s}$

$\boxed{U = 1.35 \pm 0.0049 \left[\frac{kJ}{m^2 K s}\right]}$

$\Rightarrow$ shown error on graph

Q. All future calculation will include errors

$$G_i = \frac{w_c}{N_T \pi \cdot \frac{D_i^2}{4}} = \frac{0.037\ \frac{kg}{s}}{31 \cdot \pi \frac{\left(\frac{0.21}{39.37}\right)^2}{4} m^2} = \boxed{53.4 \pm 0.43\ \frac{kg}{m^2 s}}$$

$D_H = 2.025$

$$G_H = \frac{w_s}{\frac{\pi D_H^2}{4} - \frac{N_T \pi D_i^2}{4}} = \frac{0.42\ \frac{kg}{s}}{\frac{\pi \left(2.025 in \cdot \frac{m}{39.37 in}\right)^2}{4} - 31 \cdot \frac{\left(\pi \cdot \left(\frac{0.21}{39.37}\right)^2\right)}{4} m^2}$$

$$\boxed{G_H = 388.\cancel{4}\ \frac{kg}{m^2 s}}$$

$$\frac{1}{U} = \frac{1}{1.35\ \frac{kJ}{m^2 K s}} = \boxed{0.74 \pm 0.004\ \frac{m^2 K s}{kJ}} \Rightarrow ~~show~~$$

fit into : $\frac{1}{U} = \frac{a}{G_i^b} + c + \frac{d}{G_s^e}$

$$\Rightarrow 0.74 = \frac{a}{53.4^b} + c + \frac{d}{388^e}$$

(need at least 5 data point to get all parameter fit into 36 run data. use curve_fit on python to determine).

$a = 40.09$, $b = 1.076$, $c = 0.228$, $d = 0.442$, $e = 5.94$.

calibrate unit for variables:

$$\frac{1}{U} = \left[\frac{m^2 K s}{kJ}\right] = \frac{a}{\left[\frac{kg}{m^2 s}\right]^{1.076}} \Rightarrow a = \left(\frac{m^2 K s}{kJ}\right)\left[\frac{m^2 s}{kg}\right]^{1.076}$$

$$= \left[\frac{m^{2(1+1.076)} K\, s^{(1+1.076)}}{kJ\ kg^{1.076}}\right]$$

$$\boxed{a = \left[\frac{s^{2.08}\ m^{4.16}\ K}{kJ\ kg^{1.08}}\right]}$$

so $\Rightarrow$ $a = 40.09 \left[\frac{s^{2.08}\, m^{4.16} K}{kJ\ kg^{1.08}}\right]$, $b = 1.076$, $c = 0.0228 \left[\frac{m^2 K s}{kJ}\right]$,

$d = 0.442 \left[\frac{s^{6.93}\, m^{13.86} K}{kJ\ kg^{5.93}}\right]$, $e = 5.93$

Same is done for co-current.

$\boxed{\text{figure 3 fitting}}$

~~refit~~ use parameters to find $h_i^{Exp} = \frac{1}{a} G_i^b$

$$\Rightarrow\ h_i^{Exp} = \frac{1}{40.09} \cdot 53.4^{1.076} \left[\frac{1}{\left(\frac{s^{2.08}\, m^{4.16} K}{kJ\ kg^{1.08}}\right)} \cdot \frac{kg^{1.076 \approx (1.08)}}{m^{2\cdot 1.076}\, s^{1.076 \approx (1.08)}}\right]$$

$$\boxed{h_i^{Exp} = 0.458\ \frac{kJ}{m^2 \cdot s \cdot K}}$$

h_i^{S-T} using Sieder-Tate correlation: $\mu = 1cp = 0.001 \frac{kg\, s}{m}$

$k = 0.000598\ \frac{kJ}{s \cdot m \cdot K}$, $D_i = 0.21\ in \cdot \frac{m}{39.37\, in} = 0.0053\ m$

$$h_i^{S-T} = 0.023 \cdot \frac{5.98 \cdot 10^{-4}\left[\frac{kJ}{s \cdot m \cdot K}\right]}{0.0053[m]} \cdot \underbrace{\left[\frac{0.0053[m]\ 53.4\left[\frac{kg}{m^2 s}\right]}{0.001\ \frac{kg\ s}{m}}\right]^{0.8}}_{\text{D-less}} \cdot \underbrace{\left[\frac{4.182\left[\frac{kJ}{kg\, K}\right]\ 0.001\left[\frac{kg\ s}{m}\right]}{5.98 \cdot 10^{-4}\left[\frac{kJ}{s \cdot m \cdot K}\right]}\right]^{0.33}}_{\text{D-less}}$$

$$\boxed{h_i^{S-T} = 0.46\left[\frac{kJ}{s\, m^2 K}\right]}$$

both water.

$$\left(\frac{h_i^{S-T} D_i}{k} = 0.023 \cdot \left(\frac{D_i G_i}{\mu_i}\right)^{0.8} \left(\frac{\hat{C}_p \mu}{k}\right)^{\frac{1}{3}} \cancel{\left(\frac{\mu_b}{\mu_0}\right)^{0.14}}^{\,1}\right)$$

Figure 5.
Error Propagation

$Q_c = \dot{m}_c C_p dT_c$, $Q_H = \dot{m}_H C_p dT_H$

Normalized numerator $Q = \dfrac{|Q_c| + |Q_H|}{2}$. $\dfrac{dQ}{dQ_c} = \dfrac{1}{2}$, $\dfrac{dQ}{dQ_H} = \dfrac{1}{2}$.

$$dQ = \cancel{\frac{|dQ_c| + |dQ_H|}{2}} \sqrt{\left|\frac{dQ}{dQ_c}\Delta Q_c\right|^2 + \left|\frac{dQ}{dQ_H}\Delta Q_H\right|^2}$$

$$\cancel{\Delta Q_c} = \Delta Q = \sqrt{\left|\tfrac{1}{2}\Delta Q_c\right|^2 + \left|\tfrac{1}{2}\Delta Q_H\right|^2}$$

$$= \tfrac{1}{2}\sqrt{|\Delta Q_c|^2 + \Delta Q_H|^2}$$

$$\Delta Q_c = \sqrt{\left|\frac{dQ_c}{d\dot{m}_c}\Delta \dot{m}_c\right|^2 + \left|\frac{dQ_c}{dT_c}\Delta T_c\right|^2} \qquad \frac{dQ_c}{d\dot{m}_c} = C_p dT , \quad \frac{dQ_c}{dT_c} = \dot{m}_c C_p$$

$$\Delta Q_c = \sqrt{\left[C_{p_c}(T_{c,out} - T_{c,in}) \cdot \Delta \dot{m}_c\right]^2 + \left[\dot{m}_c C_p \Delta T\right]^2}$$

$C_{p_c} = 4.182 \dfrac{kJ}{kg\,K}$, $\Delta \dot{m}_c = \text{std } m_c = 0.000297 \dfrac{kg}{s}$

$T_{c,out} - T_{c,in} = 22.39\text{ K}$ $\Delta T = 0.5$ (systematic fluctuation)

$\dot{m}_c = 0.0377 \dfrac{kg}{s}$

$$\Delta Q_c = \sqrt{\left(4.182\left[\frac{kJ}{kg\,K}\right] \cdot 22.39[K] \cdot \overset{0.0003}{\cancel{0.0377}}\left[\frac{kg}{s}\right]\right)^2 + \left[0.0377 \cancel{4.182} \frac{kg}{s} \cdot 4.182 \frac{kJ}{kg\,K} \cdot 0.5K\right]^2}$$

$= 0.084 \dfrac{kJ}{s}$

ΔQ_H derived similar. $\Delta Q_H = 0.39 \dfrac{kJ}{s}$.

$$\Delta Q = \sqrt{(0.084)^2 + (0.39)^2} = 0.398$$

Normalized error bar:

$$\frac{\Delta Q}{0.5(|Q_H| + |Q_c|)} = \frac{0.398}{3.65} = 0.11$$

Normalized data:

$$\frac{Q_c + Q_H}{0.5(|Q_H| + |Q_c|)} = \frac{3.53 - 3.76}{3.65} = \boxed{-0.0635}$$

Done for all data point.

Raw data:

Counter Current

V_s #1:

Pump speed = 35 approx. Vol. reading (AVR) = 5.10

mass (1) = 8.53 Kg time (1) = 20.05 sec

mass (2) = 8.38 Kg time (2) = 19.99 sec

cold flow	AVR=	AVR= 1.81	AVR=	AVR=	AVR=	AVR=
	mass 1 = 1.50	mass 1 = 5.87	mass 1 = 6.94	mass 1 = 14.15	mass 1 = 12.44	mass 1 = 9.78
	time 1 = 40.1	time 1 = 53.02	time 1 = 30.03	time 1 = 40.05	time 1 = 20.24	time 1 = 15.0
	mass2 = 1.52	mass2 =	mass2 =	mass2 =	mass2 =	mass2 = 12.89
	time2 = 40.0	time2 =	time2 =	time2 =	time2 =	time2 = 19.99
$T_{H,in}$	55.82	57.58	58.62	58.67	57.00	55.45
$T_{H,out}$	53.74	53.69	52.93	51.37	48.17	46.75
$T_{c,in}$	16.27	16.84	16.04	15.27	14.81	14.43
$T_{c,out}$	38.66	30.91	26.24	24.25	20.81	20.09
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6

Counter Current

V_s #2:

Pump speed = 45.19 approx. Vol. reading (AVR) =

mass (1) = 10.78 time (1) = 19.92

mass (2) = 10.86 time (2) = 20.07

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	mass 1 = 1.25	mass 1 = 4.85	mass 1 = 7.60	mass 1 = 10.08	mass 1 = 7.18	mass 1 = 9.48
	time 1 = 60.15	time 1 = 60.10	time 1 = 50.04	time 1 = 40.16	time 1 = 20.18	time 1 = 20.10
	mass2 = 1.26	mass2 =	mass2 =	mass2 =	mass2 =	mass2 =
	time2 = 60.09	time2 =	time2 =	time2 =	time2 =	time2 =
$T_{H,in}$	63.52	64.26	64.30	63.58	62.74	62.00
$T_{H,out}$	62.29	60.96	60.19	57.67	56.07	54.66
$T_{c,in}$	15.17	15.13	15.16	14.99	14.96	14.93
$T_{c,out}$	47.48	37.33	29.45	28.27	25.50	23.61
	Run 7	...	...	...	...	Run 12

Counter Current

V_s #3:

Pump speed = 50.11 approx. Vol. reading (AVR) =

mass (1) = 12.06 time (1) = 20.07

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.83	Mass 1 = 2.56	Mass 1 = 4.19	Mass 1 = 6.56	Mass 1 = 6.89	Mass 1 = 7.42
	time 1 = 30.07	time 1 = 30.13	time 1 = 29.92	time 1 = 25.07	time 1 = 20.17	time 1 = 15.21
	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 = 7.28
	time2 =	time2 =	time2 =	time2 =	time2 =	time2 = 15.10
$T_{H,in}$	63.38	64.11	64.08	63.75	63.02	62.10
$T_{H,out}$	61.98	60.90	60.11	58.27	57.00	55.28
$T_{c,in}$	15.26	15.11	15.12	15.17	15.14	15.16
$T_{c,out}$	48.06	38.24	32.74	28.52	26.42	23.86
	Run 13	...	...	...	...	Run 18

Counter Current

V_s #4:

Pump speed = 55.03 approx. Vol. reading (AVR) =

mass (1) = 10.04 time (1) = 15.0

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.51	Mass 1 = 1.88	Mass 1 = 2.81	Mass 1 = 3.84	Mass 1 = 6.02	Mass 1 = 7.42
	time 1 = 20.27	time 1 = 20.13	time 1 = 20.03	time 1 = 15.15	time 1 = 15.12	time 1 = 15.21
	Mass2 = 0.51	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 = 7.28
	time2 = 20.02	time2 =	time2 =	time2 =	time2 =	time2 = 15.10
$T_{H,in}$	58.49	57.64	57.61	57.73	58.35	60.01
$T_{H,out}$	57.57	55.10	54.37	53.53	53.13	54.05
$T_{c,in}$	15.61	15.33	15.28	15.28	15.19	15.18
$T_{c,out}$	39.95	33.58	30.58	26.82	23.96	23.50
	Run 19	...	...	...	...	Run 24

Counter Current

V_s #5:

Pump speed = 60.30 approx. Vol. reading (AVR) =

mass (1) = 10.95 time (1) = 15.04

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	mass 1 = 0.51	mass 1 = 1.39	mass 1 = 2.85	mass 1 = 4.77	mass 1 = 4.14	mass 1 = 5.23
	time 1 = 20.27	time 1 = 15.23	time 1 = 14.98	time 1 = 15.08	time 1 = 10.00	time 1 = 10.09
	mass 2 = 0.51	mass 2 =	mass 2 =	mass 2 =	mass 2 =	mass 2 = 5.20
	time 2 = 20.07	time 2 =	time 2 =	time 2 =	time 2 =	time 2 = 10.05
$T_{H,in}$	60.09	60.37	60.37	60.13	59.44	58.59
$T_{H,out}$	59.27	58.12	57.00	55.61	54.32	53.08
$T_{c,in}$	15.70	15.59	15.58	15.56	15.52	15.41
$T_{c,out}$	41.29	34.10	29.14	26.76	24.67	23.16
	Run 25 ...	...	...	...		Run 30

Counter Current

V_s #6:

Pump speed = 65.08 approx. Vol. reading (AVR) =

mass (1) = 7.97 time (1) = 10.07

mass (2) = 8.09 time (2) = 10.15

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	mass 1 = 0.33	mass 1 = 0.82	mass 1 = 1.86	mass 1 = 2.14	mass 1 = 3.50	mass 1 = 5.23
	time 1 = 25.17	time 1 = 15.05	time 1 = 15.07	time 1 = 9.99	time 1 = 10.03	time 1 = 10.09
	mass 2 =	mass 2 =	mass 2 =	mass 2 =	mass 2 =	mass 2 = 5.20
	time 2 =	time 2 =	time 2 =	time 2 =	time 2 =	time 2 = 10.05
$T_{H,in}$	56.90	56.07	55.81	55.81	55.97	56.84
$T_{H,out}$	56.47	54.64	53.34	52.68	52.03	52.01
$T_{c,in}$	15.61	15.46	15.34	15.73	15.30	15.31
$T_{c,out}$	40.51	36.32	30.67	26.92	24.37	22.89
	Run 31 ...	...	...	...		Run 36

Co-Current

V_s #1:

Pump speed = 65.08 approx. Vol. reading (AVR) =

mass (1) = 7.97 time (1) = 10.07

mass (2) = 8.09 time (2) = 10.15

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = .47	Mass 1 = 1.01	Mass 1 = 2.12	Mass 1 = 2.16	Mass 1 = 3.51	Mass 1 = 6.14
	time 1 = 30.06	time 1 = 15.08	time 1 = 15.14	time 1 = 10.20	time 1 = 10.05	time 1 = 10.04
	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 = 6.18
	time2 =	time2 =	time2 =	time2 =	time2 =	time2 = 10.12
$T_{H,in}$	61.30	62.26	62.26	62.12	61.69	60.88
$T_{H,out}$	60.60	60.19	59.32	58.51	57.30	55.41
$T_{c,out}$	52.25	39.38	32.42	28.84	25.76	22.53
$T_{c,in}$	16.16	15.94	15.95	15.89	15.86	15.71
	Run 37	...	...	...	...	Run 42

Co-Current

V_s #2:

Pump speed = 60.16 approx. Vol. reading (AVR) =

mass (1) = 7.38 time (1) = 10.15

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.42	Mass 1 = 1.14	Mass 1 = 1.24	Mass 1 = 2.51	Mass 1 = 4.12	Mass 1 = 6.14
	time 1 = 20.04	time 1 = 15.07	time 1 = 10.14	time 1 = 10.12	time 1 = 10.09	time 1 = 10.04
	Mass2 = 0.39	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 = 6.18
	time2 = 20.05	time2 =	time2 =	time2 =	time2 =	time2 = 10.12
$T_{H,in}$	57.90	57.39	57.11	57.22	57.50	59.58
$T_{H,out}$	57.04	55.43	54.58	53.68	53.09	53.94
$T_{c,out}$	46.32	34.58	30.22	25.61	23.15	22.10
$T_{c,in}$	15.72	15.57	15.46	15.41	15.44	15.55
	Run 43	...	...	...	...	Run 48

Co-Current

V_s #3:

Pump speed = 55.30 approx. Vol. reading (AVR) =

mass (1) = 6.74 time (1) = 10.14

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.42	Mass 1 = 1.10	Mass 1 = 2.09	Mass 1 = 4.36	Mass 1 = 5.92	Mass 1 = 8.03
	time 1 = 20.09	time 1 = 15.15	time 1 = 10.03	time 1 = 10.12	time 1 = 10.09	time 1 = 10.13
	Mass2 = 0.39	Mass2 =	Mass2 =	Mass2 =	Mass2 =	Mass2 = 7.99
	time2 = 20.05	time2 =	time2 =	time2 =	time2 =	time2 = 10.12
$T_{H,in}$	59.44	60.01	59.99	59.67	58.82	57.75
$T_{H,out}$	58.46	57.67	56.15	54.41	53.01	51.03
$T_{c,out}$	49.16	36.50	27.77	23.65	22.03	20.82
$T_{c,in}$	15.81	15.69	15.74	15.67	15.80	15.32
	Run 49	...	...	...	...	Run 54

Co-Current

V_s #4:

Pump speed = 50.11 approx. Vol. reading (AVR) =

mass (1) = 6.11 time (1) = 10.18

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.34	Mass 1 = 1.22	Mass 1 = 1.88	Mass 1 = 3.27	Mass 1 = 5.58	Mass 1 = 8.03
	time 1 = 20.0	time 1 = 15.13	time 1 = 10.15	time 1 = 10.10	time 1 = 10.19	time 1 = 10.13
	Mass2 = 0.31	Mass2 = 1.21	Mass2 =	Mass2 =	Mass2 =	Mass2 = 7.99
	time2 = 20.12	time2 = 15.12	time2 =	time2 =	time2 =	time2 = 10.12
$T_{H,in}$	56.05	55.27	54.91	54.92	55.23	56.59
$T_{H,out}$	55.20	52.92	51.39	50.43	49.64	49.54
$T_{c,out}$	47.79	33.11	26.41	23.43	21.20	20.42
$T_{c,in}$	15.43	15.28	15.28	15.25	15.23	15.18
	Run 55	...	...	...	...	Run 60

Co-Current

V_s #5:

Pump speed = 45.12 approx. Vol. reading (AVR) =

mass (1) = 5.66 time (1) = 10.50

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.34	Mass 1 = 0.82	Mass 1 = 1.96	Mass 1 = 3.01	Mass 1 = 5.16	Mass 1 = 7.95
	time 1 = 20.0	time 1 = 20.14	time 1 = 11.15	time 1 = 10.03	time 1 = 10.17	time 1 = 10.06
	Mass2 = 0.31	Mass2 =	Mass2 =	Mass2 =	Mass2 = 5.16	Mass2 = 7.85
	time2 = 20.12	time2 =	time2 =	time2 =	time2 = 10.06	time2 = 10.00
$T_{H,in}$	59.69	60.78	60.76	60.44	59.83	58.07
$T_{H,out}$	58.65	58.69	56.29	54.90	52.99	50.16
$T_{c,out}$	32.21	42.79	28.88	25.42	22.79	20.77
$T_{c,in}$	15.64	15.64	15.66	15.65	15.59	15.40
	Run 61	...	...	...	...	Run 66

Co-Current

V_s #6:

Pump speed = 35.04 approx. Vol. reading (AVR) =

mass (1) = 6.18 time (1) = 15.15

mass (2) = time (2) =

	AVR=	AVR=	AVR=	AVR=	AVR=	AVR=
	Mass 1 = 0.95	Mass 1 = 2.31	Mass 1 = 4.27	Mass 1 = 4.56	Mass 1 = 6.02	Mass 1 = 7.95
	time 1 = 21.00	time 1 = 15.15	time 1 = 15.15	time 1 = 10.11	time 1 = 10.13	time 1 = 10.06
	Mass2 =	Mass2 =	Mass2 =	Mass2 = 4.59	Mass2 =	Mass2 = 7.85
	time2 =	time2 =	time2 =	time2 = 10.08	time2 =	time2 = 10.00
$T_{H,in}$	54.19	53.48	53.70	53.74	54.77	55.89
$T_{H,out}$	51.93	49.35	47.86	47.02	46.91	46.63
$T_{c,out}$	37.07	26.48	23.36	21.53	20.71	19.90
$T_{c,in}$	15.60	15.42	15.41	15.47	15.45	15.19
	Run 67	...	...	...	...	Run 72