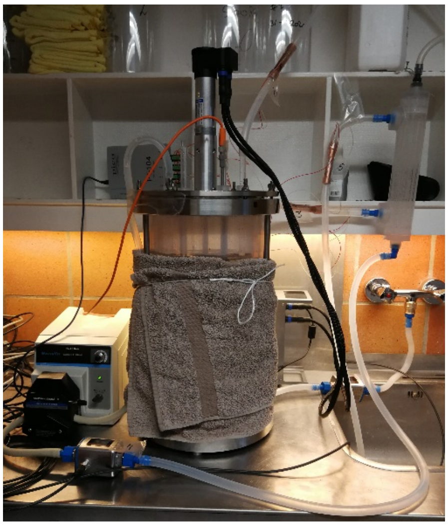
Thermal experiment

1 Abstract

A 13-liter Single-Use-Mixer (SUM) inserted into a Re-Useable-Jacket (RUJ) in series with a single-use heat-exchanger. All standard parts from www.CerCell.com are subject to be heated up with hot water. An analysis is made about the speed it can be done and what maximum temperature can be obtained.



2 Introduction

Before the experiments it is a good idea to have an idea of how much power and energy actual is needed. For the experiments water is used both as media and as heat. For water the specific heat is:

C_p= 4.187 kJ/kgK

The RUJ has a volume of 21 liters and contain the SUM of 13 liter it gives the heat capacity:

C=21kg*4.187 kJ/kgK=87.927kJ/K

If the target is to heat up from 0 to 80 °C the following energy is needed:

E=C(T_{end} - T_{start})=87.927kJ/K * 80K ≈ 7MJ

If it is assumed that the 80 °C is reach after 30 min the average power needed would be:

P=7MJ/1800s=3.9kW

The calculation above is without any consideration to the loss in material and to the air.

With heating by water the thermal conductivity between the heat and the media becomes important. In the ideal situation the SUM is surrounded by a fixed temperature T which of course must be >80 °C if the former is the target. In the following the system is approximated to an imaginary wall of unknown material between the heat and the SUM with the thickness of 1cm. The heat flux is:

$$\varphi = -k\frac{dT(x)}{dx} = -k\frac{T_{SUM} - T}{1cm}$$

k is the thermal conductivity. dT(x) is the difference between the heat and the temperature in the SUM. When the temperature in the SUM rises this difference will gradual become smaller. dx is as explained before 1cm. The power added to the SUM with the surface area of A is:

$$P = \varphi A$$

Together an equation for the temperature for SUM over time t can be written:

$$\frac{dT_{SUM}}{dt}C_{SUM} = \varphi A = -k\frac{T_{SUM} - T}{1cm}A \Leftrightarrow$$

$$\frac{1}{T_{SUM} - T}dT_{SUM} = -k\frac{A}{C_{SUM} * 1cm}dt$$

This can be solved to:

$$ln|T_{SUM} - T| = -k\frac{A}{C_{SUM} * 1cm}t + h$$

$$T_{SUM} - T = \pm e^{-(kA/C_{SUM})t/1cm}e^h$$

And since T_{SUM}<T always

$$T_{SUM} = T - e^{-(kA/C_{SUM})t/1cm}e^h$$

h is a constant which determine the value of T_{SUM} at t=0 which if T_{sum}=0 must mean that:

h=ln(T)

A new constant k_x for the above system can be introduced with the value:

$$k_x = kA * kJ/(1cm * K)$$

Though the volume of SUM is 13 liter it will only be filled to 10 liters. Which means:

C_{SUM}=10kg*4.187 kJ/kgK=41.87kJ/K

All together gives

$$T_{SUM} = T(1 - e^{-(k_x/41.87)t})$$

The problem is to find k_x.

3 Setup

The Figure 1 shows the setup. The room temperature is 23 °C and the water was only 13 °C to begin with. Pressure from the heater must be low (<1.2Bar) in order not to destroy the RUJ.

If the heat has a high temperature >50 °C, isolation of all horses, RUJ and exchanger becomes a necessity.

It is important that all hoses to pump and flow sensors are fully filled with water or they will not work.

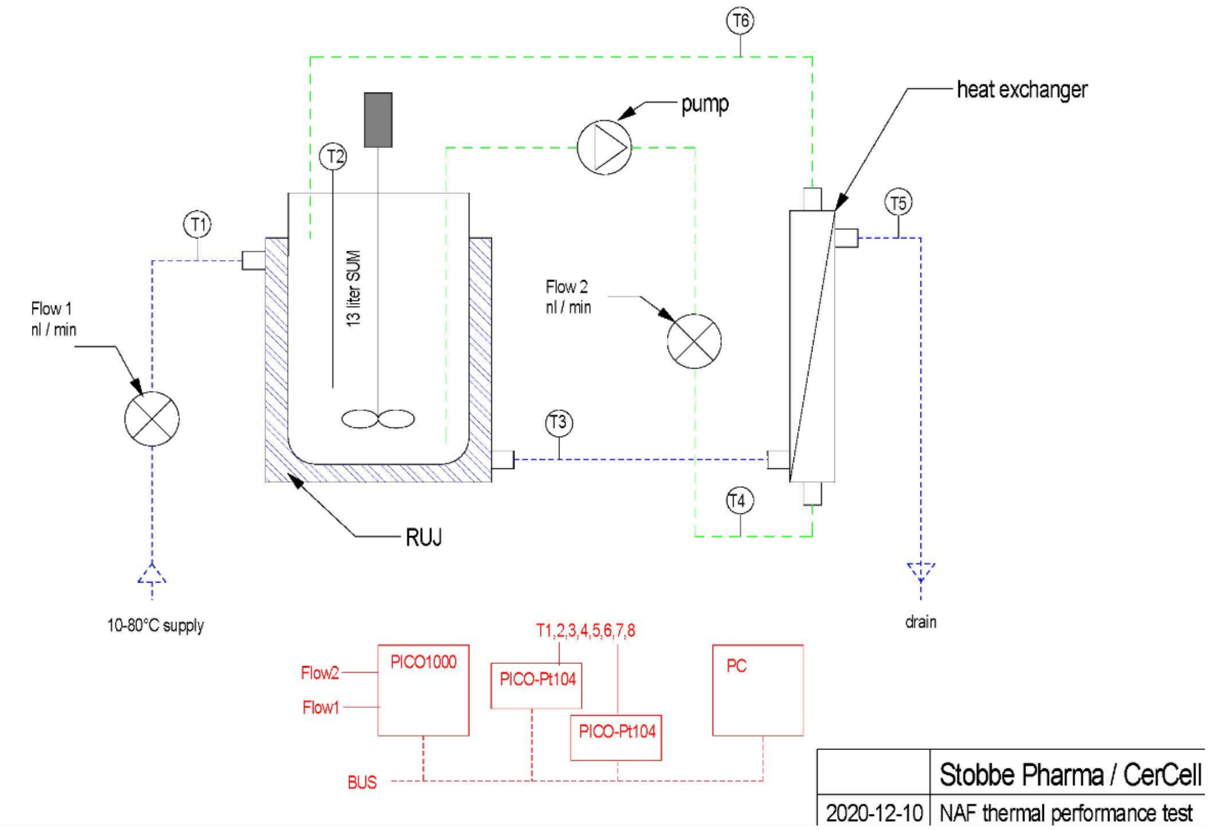


Figure 1 - Setup heating of SUM containing 10 liter water. Both circuits arranged in series.

The supply heat comes from a 10kW heater which heats up water from 12 °C during all the experiments. There is in other words no recirculation. The SUM was equipped with a stator and the impeller rotated with 150rpm. The pump was set at 0.5 liter/min.

3.1 Constraints on this setup

Though the supply heater can give 10kW there is a thermostat which offer a max temperature of 62-64 °C. A calculation shows that the max flow at that temperature cannot be more than 3 liters, in praxis less because of loss in the system.

The choice of peristaltic pump limited the flow of the media to 0.5-1 liter/min circulation.

4 Experiments

First it was tried to heat with 3.5 liter/min flow until the heater gives in, and because of that a second experiment was made with a lower heat flow. The sampling rate was 1 second.

4.1 Heat flow 3.5 liter/min

First the heating curves are explained.
The yellow is the heat in (T1). As it can be seen it can only sustain the temperature (65 °C) for 15 minutes before the heater gives in. The purple T3 seems to reach a temperature at max 59 °C because of loss in the system (And low flow rate). At the beginning T3 is well below T1 and one could think it is caused by heat dissipation to the SUM, but is mostly caused by the cold water in the RUJ, which has to be replaced.

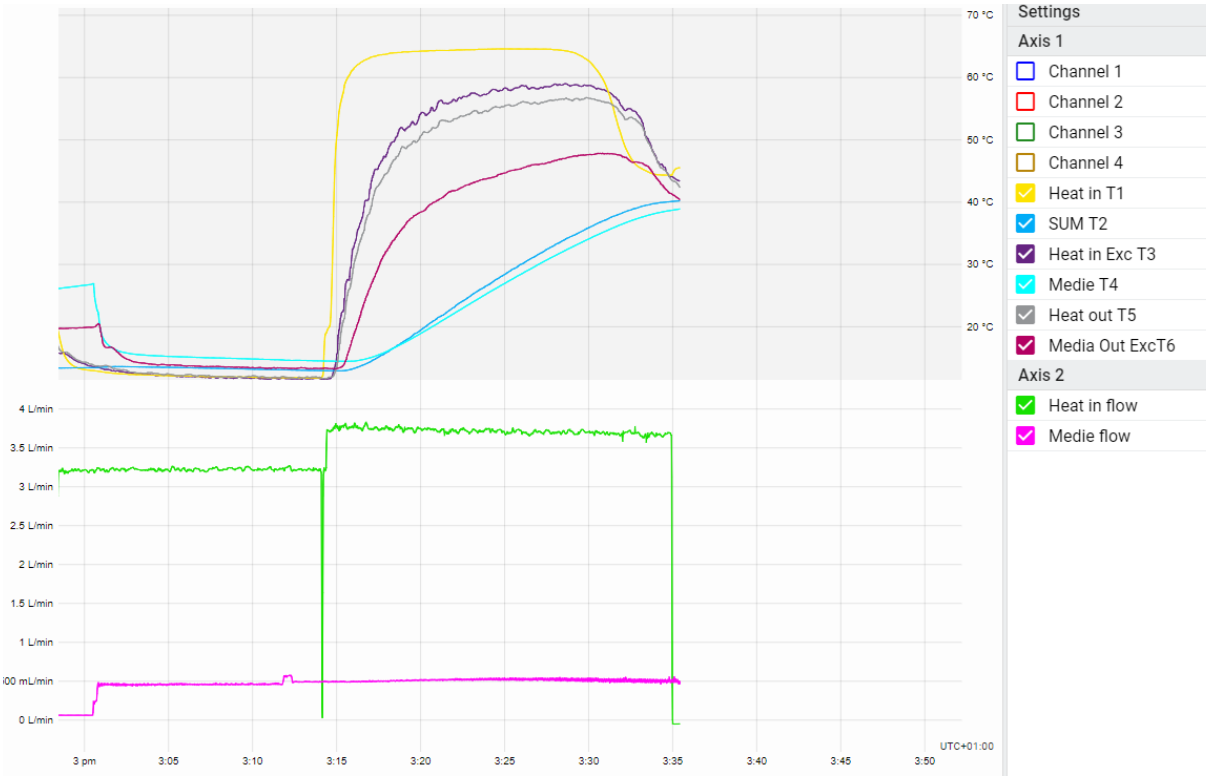


Figure 2 - Heating with 3.5 L/min hot water supply.

The volume in the RUJ is 21 L-13L=8 L. And the flow I 3.5L/min so it will take 3 minutes.

Now the media flow curves are explained.
The blue T2 is the SUM temperature. The magenta T4 is its way out to the heat exchanger, as it can

be seen it is a little bit lower than T2 also because of loss which grows with increasing temperature. It is interesting since there is no more than 0.5m hose from the SUM to the sensor, but it was not isolated. Out of the exchanger (Red T6) the media temperature can be almost as much as 20 °C higher than input while the heating temperature only drops a little. That indicates that even with this setup a larger exchanger and increased media flow could significantly increase the speed. A media flow of 0.5L/min means that the SUM of 10 L will first be replaced after 20 minutes.

4.2 Heat flow 1.5 liter/min

The first thing to notice on Figure 3 is that it follows the same pattern to begin with as in the previous experiment, but it is somewhat slower, but the heater can supply the heat continuously. In the previous example it took the SUM 6 minutes to go from 20 to 30 °C in this experiment it took 9 minutes. The reason is that the heat temperature into h-exchanger is much lower at the beginning.

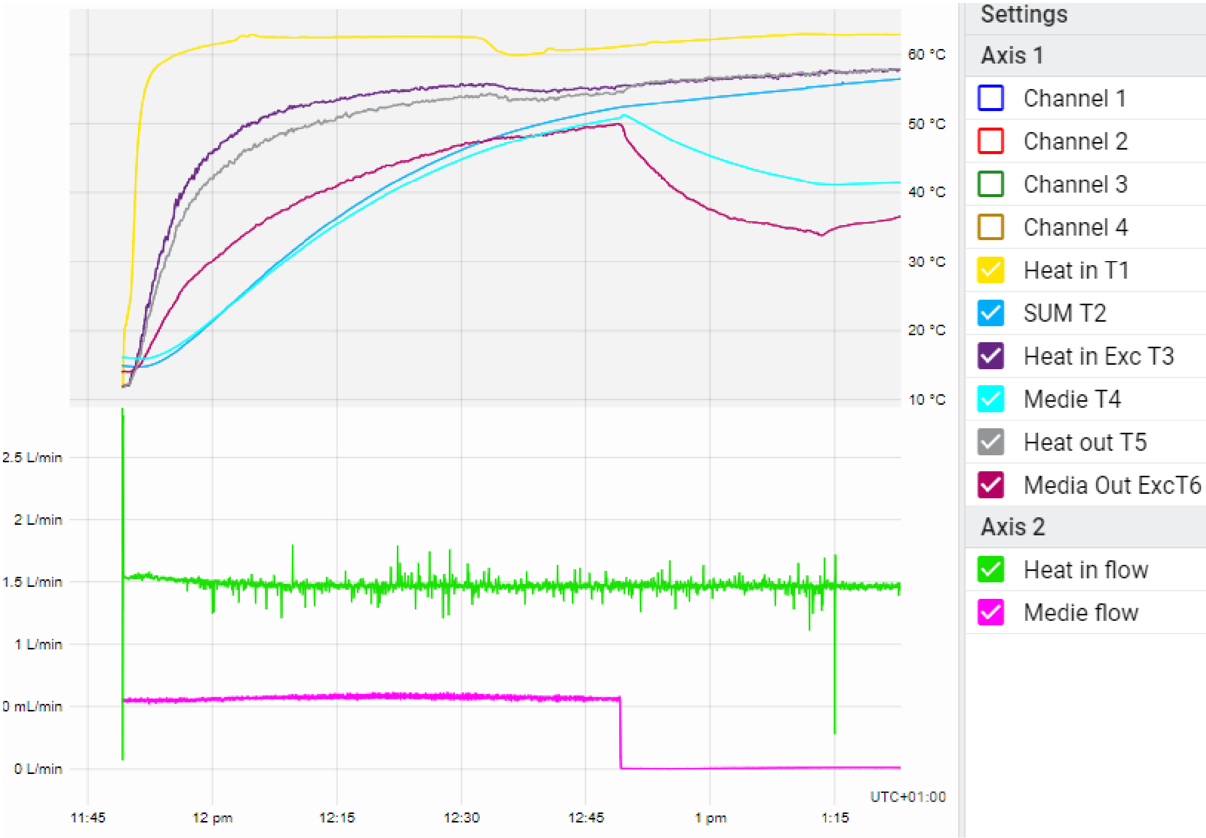


Figure 3 - Heating with 1.5 L/min hot water supply.

Because the heater could sustain its temperature the experiment continued until a stable temperature for SUM at 57 °C was reached. At a certain point at 12:49 the h-exchanger stopped working due to loss in the system and the pump was because of that stopped. Despite the fact the heat in the exchanger was 5 °C above the media temperature it could not dissipate heat into the media. The RUJ in this experiment was somewhat isolated with towels and is more compact than the accessories (exchanger hoses pump sensors) attached to it so it could continue heat up the SUM. However, eventually at 57 °C the added heat equaled the loss, and the experiment was stopped.

5 Analysis

From 2 (The introduction) it is stated that:

$$T_{SUM} = T(1 - e^{-(k_x/41.87)t})$$

That is the assumption of constant T (Which is T 3) during the whole process, that is not the case, but the first experiment comes closest. Second the equation was determined by a start point a 0 °C at t=0, that is not case either but that is easy to correct by introducing a constant z. Furthermore, for the benefit of this analysis it makes sense to split k_x in two parts one for the RUJ and another one for the exchanger.

$k_x = k_{RUJ} + k_{Exc}$

All together gives:

$$T_{SUM} = T(1 - ze^{-((k_{RUJ}+k_{Exc})/41.87)t})$$

k_x is estimated from a fix point at 35 °C (t_{35})

Without further explanation and for simplicity the k_{RUJ} and k_{Exc} is given, based on the data from the start to, to 35 °C is reached.

	T_0	T	z	t_{35}	k_x	k_{RUJ}	k_{Exc}
Experiment 3.5 L/min	12.8 °C	58.7 °C	0.78	14 min	1.98	1	0.98
Experiment 1.5 L/min	14.6 °C	55.6 °C	0.74	21 min	1.38	0.53	0.85

The reason why the exchanger contributed so little in the 1.5L/min experiment was caused by the low flow. The heat was cooled much more down through the RUJ than in the first experiment. Although the difference in k_x is due to the fact, that the calculation is based on a constant T and that is not what happens. It will require a great deal of energy to ensure a constant T especially at the beginning of the process, but 3.5 L/min is of cause better in that respect than 1.5L/min.

The loss is based on difference between T1 and T3 when somewhat stable T2 temperature reached can only be calculated for 1.5L/min:

1.5 L/min : (1.5L/60s)(62.8-57.3) °C*4.187=575W

The room temperature was 23 °C so the difference to T1 was 39 °C. If T1 is 90 °C the loss would be

$Loss_{90}$=((90-23)/39)*575W=988W

With a 5 °C drop in temperature. In other word if more than 988W is added to the system a temperature at 85 °C can be reached in this not so proper isolated system. What would that require in flow:

(x/60s)5 °C*4.187J/K=988W gives x=2.8L/min

With T=85 °C with the constants found in experiment 3.5 liter gives and with a start temperature at 0 gives:

$$T_{SUM} = 85\ °C(1 - e^{-(1.98/41.87)t}) = 85\ °C(1 - e^{-0.0473t})$$

An ideal picture can be seen at Figure 4 if the 8 liter cold water in the RUJ at the beginning is ignored. 12% is added to the use of power to compensate for the heat needed to heat up 10 kg of stain less steel. A calculation of the drop of T3 was also made, and is can be seen in average it is not more than 10% so the approximation of constant T seems to be acceptable.

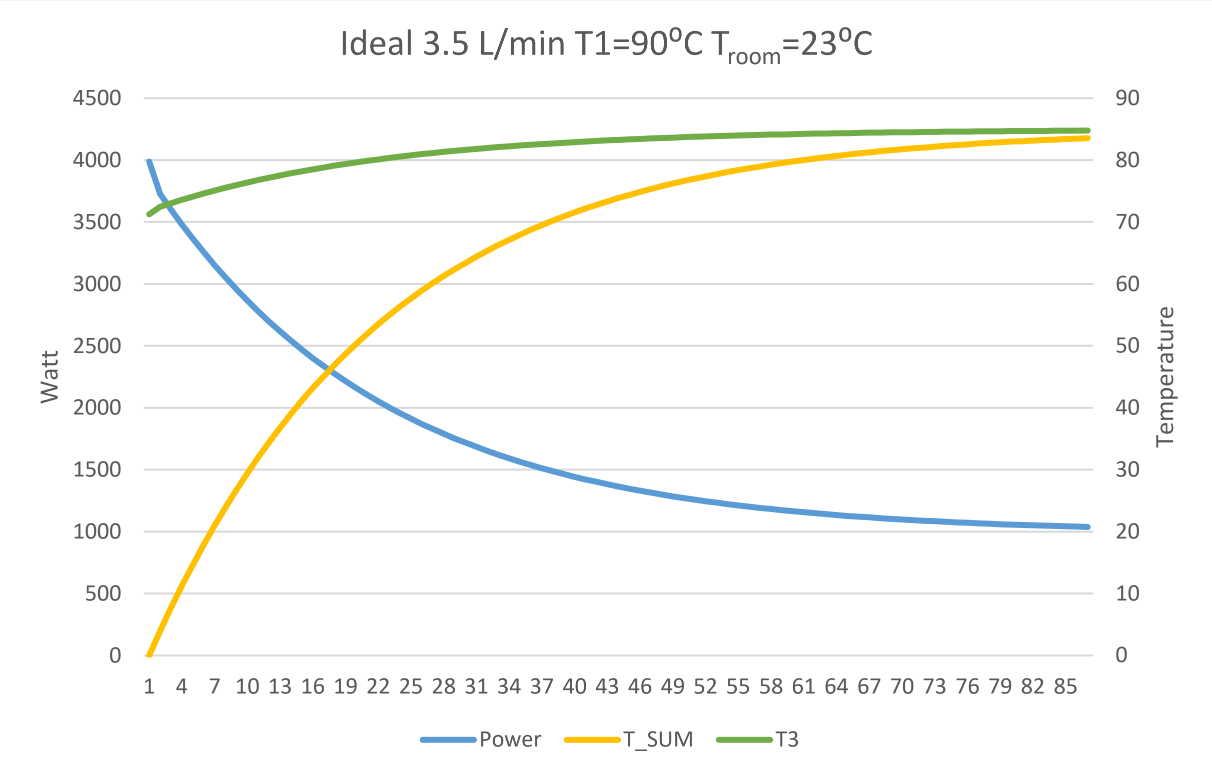


Figure 4 - T3 will be 0 at the beginning in real scenario. Time is in minutes

6 Conclusion

With a RUJ combined with a standard heat-exchanger and with proper isolation it is possible to reach 85°C media if the system is supplied with plenty of 90 °C hot water.

During the first 3 minutes, the hot water temperature will drop significantly until the initial cold water in the RUJ has been replaced. Target of 80 °C media can be reach in 65 minutes.

Reduced heating time can be obtained:

- with bigger and optimized heat-exchanger
- by increased hot water mass flow
- with higher power of hot water source

Furthermore - double hot water source power does not decrease the time with a factor 2 !

Proper isolation means that especially RUJ, all hoses and heat-exchanger must be insulated avoiding switching of the pump near the target temperature.

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