Temperature Control for ResonantAcoustic® Mixing Processes

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ABSTRACT

The standard jacketed vessel mixing container for the LabRAM® serves as a heat exchanger to control mixture temperatures during mixing operations. An instrumented jacketed vessel was used to quantify heat exchanger characteristics. The experimental results indicate the LabRAM® environment improves the overall heat-transfer coefficient of the vessel.

Introduction

Many mixing applications require the control of the mixture temperature, either by removing heat that is generated within the mixture or by adding heat to maintain an elevated mix temperature. Resodyn Corporation offers a jacketed vessel for temperature control. This jacketed vessel, fitted with a custom lid, was instrumented with temperature probes and thermocouples to allow for quantitative characterization of the jacketed vessel heat transfer capabilities.

Experimental

Resodyn Corporation designed a jacketed vessel for use on the Resodyn Corporation LabRAM® to provide both cooling and heating to materials mixed in the vessel during RAM operations. The jacketed vessel was modified by the addition of thermocouples to measure inlet and outlet temperatures of water passing through the jacket. (See Figure 1.) This is referenced as the jacket circuit. Water circulation was added to the vessel itself (vessel circuit) to allow hot water to flow into and out of the vessel. This provided the heat source, while the flow of cold water through the jacket provided cooling. The inlet and outlet temperatures of the vessel circuit were also monitored. (See Figure 2.)

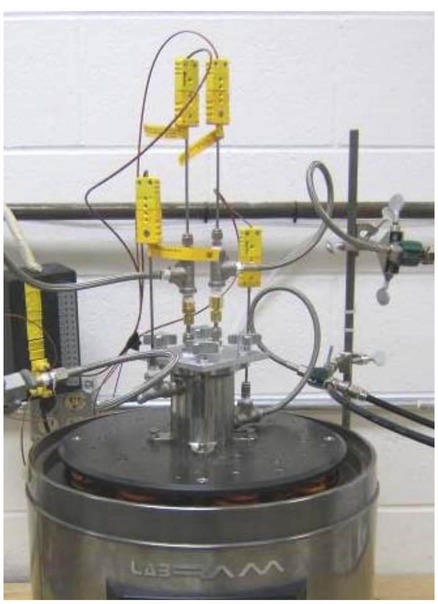

Figure 1. Instrumented Jacketed Vessel on LabRAM®.

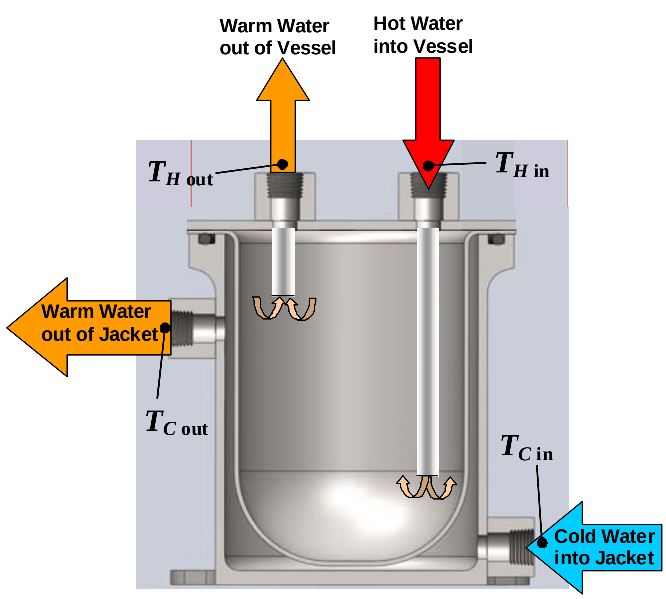

Figure 2. Hot and Cold Water Circulation Circuits for Jacketed Vessel.

The cold water was supplied by city tap water and the hot water was supplied by a residential hot water heater. RAM mixing typically utilizes a headspace in the mix vessel to allow for expansion, contraction and overall motion of material as it is subjected to the acoustic mixing influence. Therefore, headspace was incorporated into both the vessel and jacket by injecting pressurized air into the water stream. The injected air created a headspace fraction in both continuous flow circuits. Figure 3 illustrates the effect low g acceleration has on water air mixtures subject to ResonantAcoustic® mixing. The accelerated, two phase regime provides a highly turbulent flow between the vessel wall and the fluids (both liquid and air), as well as providing a high degree of mixing within the two phase fluid system. As such, heat transfer from the vessel and movement of heat into the fluids within the mix vessel and in the cooling/heating jacket is very high.

Figure 3, Gas-Liquid Mixing, Air and Water at 20 g

The experimental setup allowed for a broad parametric study of the jacketed vessel. The acceleration of the LabRAM® could be varied, the flow rate of water in the jacket and vessel circuit could be adjusted and the fraction of air injected could be altered. Two parameters, acceleration and headspace were varied for the experiments described here. The fluid motion in the circuits was produced by the overall flow rates and the acceleration magnitude of the 60 Hz (nominal) vibration of the LabRAM®.

Constant Flow Variable Acceleration

In the first experiment, the water flow rates for the jacket and vessel circuit were fixed. The amount of air injection was also fixed resulting in a consistent headspace. Only acceleration was varied. The experimental conditions are listed in Table 1. Once the water flows were set, the data acquisition system was initiated and temperature data was recorded as the system was operated at different accelerations.

Constant Acceleration Variable Headspace

In the second experiment, the amount of air injected into the jacket circuit was varied while the water flows in the jacket and in the vessel circuit were kept constant. All tests were conducted at a constant acceleration. The experimental conditions are listed in Table 1. For each experimental condition, the water and air flow parameters were set, the LabRAM® was started and the system was allowed to stabilize before recording temperatures.

Table 1. Experimental Parameters for Jacketed Vessel with Hot and Cold Water Circuits

Volume Flow									
Water		**Air @ 255 kPa**							
Jacket (m^3/s)	Vessel (m^3/s)	Jacket (m^3/s)	Vessel (m^3/s)	Accel. (g's)	Area [a] (m^2)	$c_{P,Water}$ (J/kg K)	$c_{P,Air}$ (J/kg K)	ρ_{Water} (kg/m^3)	ρ_{Air} [b] (kg/m^3)
Constant Flow Variable Acceleration									
$3.2x10^{-5}$	$3.2x10^{-5}$	$5. x10^{-5}$	$5. x10^{-5}$	0 - 53	0.0185	4,181	1005	996	3.27
Constant Acceleration Variable Headspace [b]									
$3.2x10^{-5}$	$3.2x10^{-5}$	0 or $5.0x10^{-5}$	0 or $5.0x10^{-5}$	20	0.0185	4,181	1005	996	3.27

a) Heat transfer area = vessel area in contact with jacket water

b) Air density at 255 kPa and 19°C

c) The air fraction for $5.0x10^{-5}$ m^3/sec air addition is 61%

Results and Discussion

Data Reduction

The test parameters and temperature data were used to calculate the overall heat-transfer coefficient of the system, U (W/m^2 K):

$$U = \frac{q_{average}}{\Delta T_{lm} \times A} \tag{1}$$

$$q_{average} = \frac{q_{Vessel} - q_{Jacket}}{2} \tag{2}$$

$$q_{Vessel} = \left(T_{H,in} - T_{H,out}\right) \cdot C_{P,Vessel} \tag{3}$$

$$q_{Jacket} = \left(T_{C,out} - T_{C,in}\right) \cdot C_{P,Jacket} \tag{4}$$

$$C_{P,Vessel} = \left(c_{P,Ait} \times \dot{m}_{Air} + c_{P,Water} \times \dot{m}_{H2O}\right)_{Vessel} \tag{5}$$

$$C_{P,Jacket} = \left(c_{P,Ait} \times \dot{m}_{Air} + c_{P,Water} \times \dot{m}_{H2O}\right)_{Jacket} \tag{6}$$

$$\dot{m} = \dot{V} \cdot \rho \tag{7}$$

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\Delta T_2 / \Delta T_1\right)} \tag{8}$$

$$\Delta T_1 = T_{H,in} - T_{C,out} \tag{9}$$

$$\Delta T_2 = T_{H,out} - T_{C,in} \tag{10}$$

$$AF = \frac{\dot{V}_{air}}{\dot{V}_{air} + \dot{V}_{H_2O}} \tag{11}$$

where:

U = overall coefficient (W/m^2 K)

q = heat transfer (W)

T = Temperature (K) (locations defined by Figure 2)

A = Heat transfer Area (m^2)

c_P = Heat Capacity (W/K)

AF = air fraction

$\dot{V}$ = volume flow rate (m^3/s)

$\dot{m}$ = mass flow rate (kg/s)

ρ = density (kg/m^3)

Results for Constant Flow Variable Acceleration

The data collected for constant flow variable acceleration is listed in Table 2. This data was reduced per Equations 1-10 above and summarized in Figure 4. Note that the definition for the log mean temperature, (ΔT_{lm}) is based on a counter flow definition for a single pass tube and shell heat exchanger.

Results for Constant Acceleration Variable Headspace

The data collected for constant acceleration and variable head space is listed in Table 3. This data was reduced per Equations 1-10 above. The air fraction in the flow (Equation 11) was calculated based on the volume flow rate data in Table 1. The results are summarized in Figure 5.

Table 2. Temperature Data for Constant Flow, Variable Acceleration Experiment

Acceleration (g's)	$T_{C,in,Jacket}$ (°C)	$T_{C,out,Jacket}$ (°C)	$T_{H,in,Vessel}$ (°C)	$T_{H,out,Vessel}$ (°C)
0	5.25	12.10	37.12	30.45
10	5.26	12.60	37.13	29.82
20	5.18	11.65	32.76	26.46
25	5.19	12.79	35.05	27.69
35	5.17	13.05	34.61	26.99
45	5.23	13.17	34.02	26.19
53	5.05	10.04	31.80	27.05

Table 3. Temperature Data for Constant Acceleration, Variable Headspace Experiment

Air Flow in Both Circuits (m^3/sec)	$T_{C,in,Vessel}$ (°C)	$T_{C,out,Vessel}$ (°C)	$T_{H,in,Jacketl}$ (°C)	$T_{H,out,Jacketl}$ (°C)
0	9.79	16.42	52.46	45.43
2.45 x10^{-5}	10.09	19.78	49.69	39.73

Note: Constant Acceleration = 20 g's

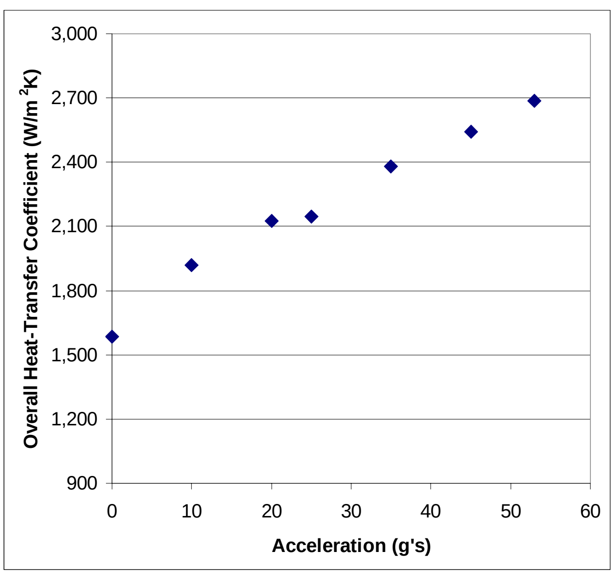

Figure 4. Overall Heat Transfer Coefficient as a Function of LabRAM Acceleration for Constant Water and Air Flow Conditions

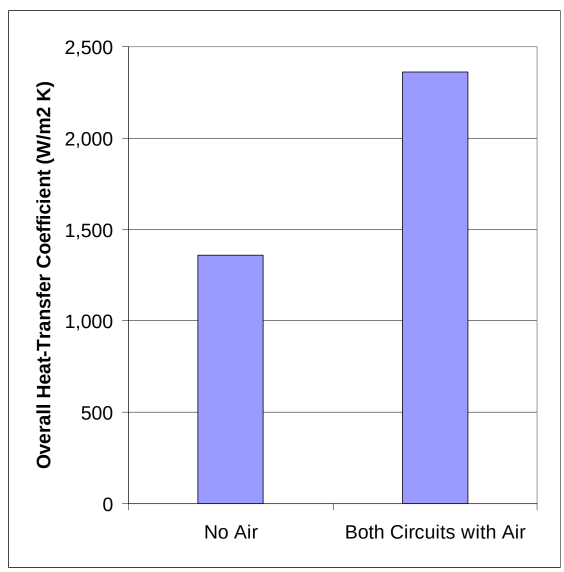

Figure 5. Overall Heat-Transfer Coefficient as a Function of Added Air (Which Creates Headspace in the Jacketed Vessel) and Constant Acceleration

Summary and Conclusions

An experimental evaluation of the LabRAM® jacketed vessel shows the RAM conditions (nominally 60 Hz vibrations with acceleration dependent amplitudes) do not hinder the heat exchange function of the jacketed vessel. In fact, when air is injected into the jacket space (to provide mixing headspace) the overall heat-transfer coefficient of the system increases significantly. Increasing LabRAM® acceleration also increased the overall heat-transfer coefficient. The comparison of overall heat-transfer coefficient in Figure 5 shows the two-phase mixing that occurs in the jacket enhances heat transfer more effectively then slug flow of water alone.