Performance of an Entegris pHasor® X Heat Exchanger in Cabot Semi-Sperse® 12

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Introduction

- Heat exchangers can be used to efficiently remove heat from liquid delivery systems, such as those incorporating centrifugal pumps.
- The heat exchanger evaluated is constructed entirely of PFA to provide
  - High purity
  - Chemical compatibility
- Even though it is constructed of PFA, it is efficient at removing heat with an acceptable pressure drop.
- However, in slurry applications, there is concern that the heat exchanger may damage the slurry or clog.

Introduction

- Materials of construction and design are important:
  - Thermal conductivity
  - Corrosion resistance
  - Capable of withstanding thermal stresses and high pressures
- Since PFA has poor thermal conductivity properties relative to most metallic heat exchangers
  - Tube thickness must be thin
  - Exchanger must be well designed to prevent flow channeling and streaming
  - Surface area must be large
- Tradeoffs:
  - Reducing the tube thickness reduces the operating temperature and pressure rating of the device
  - Increasing the surface area increases cost and size of the device

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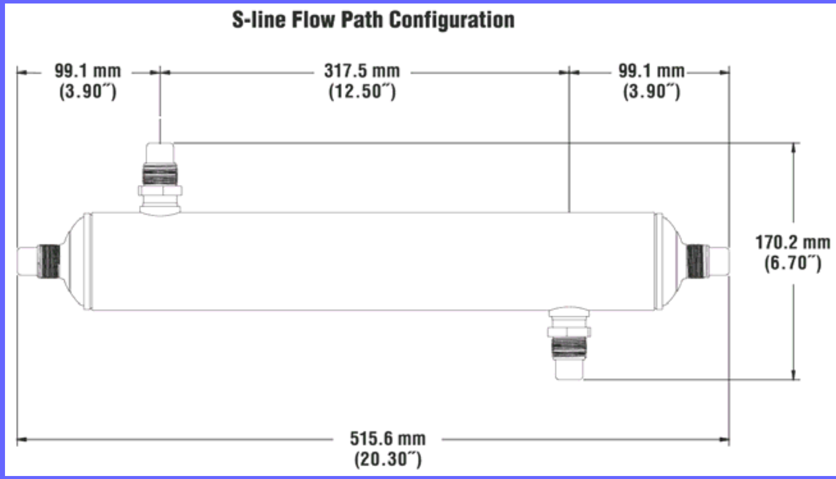
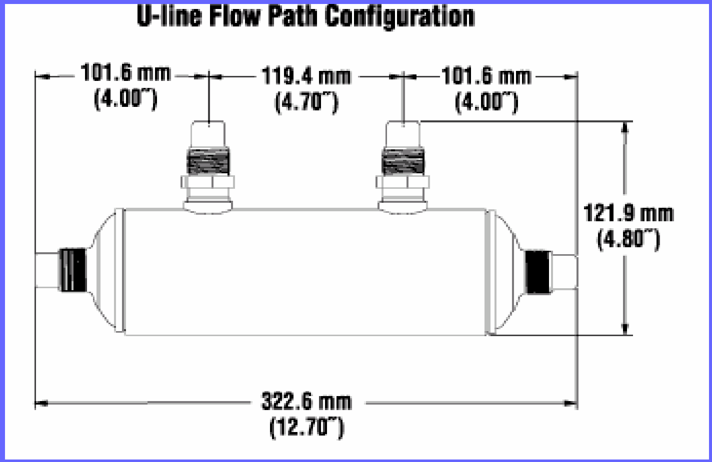
Heat exchanger configurations





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Experiments performed in water

- Measurement of differential pressure drop (Δ P) in the tube and shell as a function of flow rate.
  - PHX03U (U configuration, short: surface area = 0.3 m^2)
  - PHX08S (S configuration, long: surface area = 0.8 m^2)
  - PHX08U (U configuration, long: surface area = 0.8 m^2)
- Measurement of heat transfer coefficients at a series of flow rates for 3 different heat exchangers.
  - PHX03U
  - PHX08S
  - PHX08U

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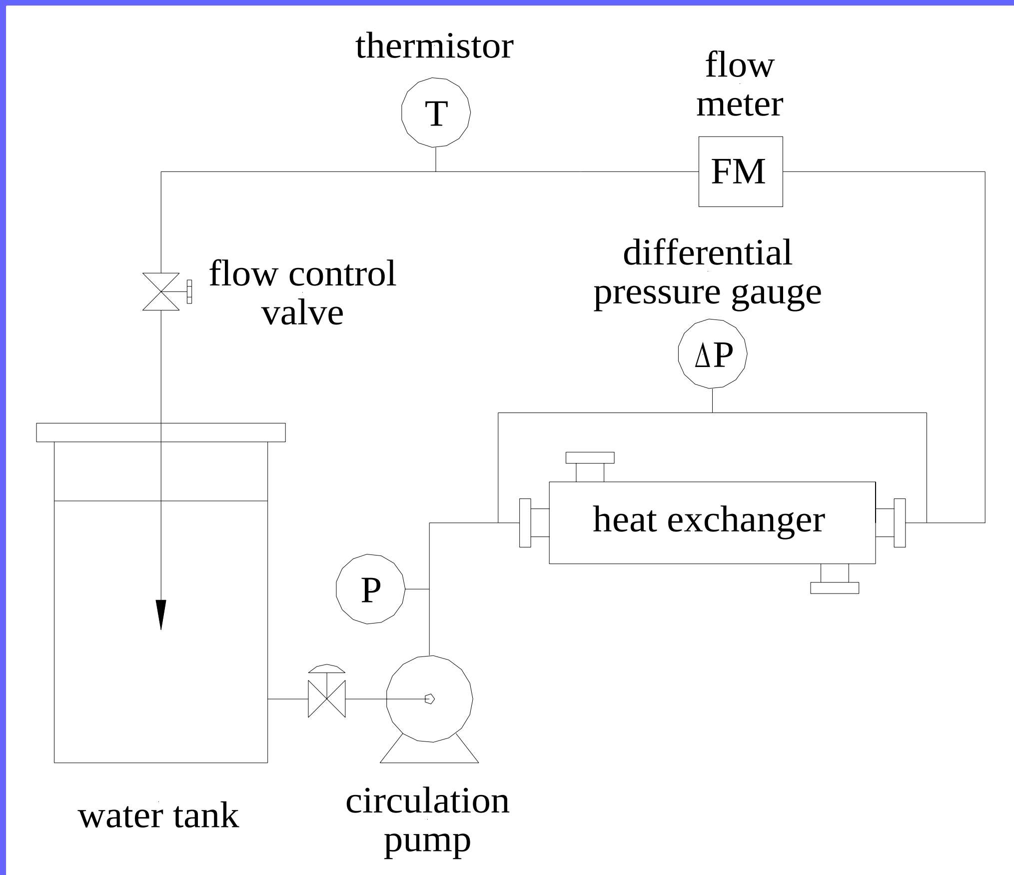
Schematic of pressure drop versus flow rate test system



Calculation of heat transfer coefficient

$$U = \frac{Q\, c\, \Delta T_{tube}}{A\, \Delta T_{ln}}$$

- where:
  - U = heat transfer coefficient (Btu/hr/ft^2/°F)
  - Q = flow rate on the tube side (lb/hr)
  - c = specific heat of water (Btu/lb/°F) = 1.0
  - $\Delta T_{tube} = T_{tube\ in} - T_{tube\ out}$ (°F)
  - A = surface area of heat exchanger (ft^2)
  - ΔT_{ln} = logarithmic mean temperature difference = $[\Delta T_0 - \Delta T_L]/[\ln(\Delta T_0/\Delta T_L)]$
    - where: ΔT_0 and ΔT_L = temperature differences between the hot and cold fluids at the two ends of the heat exchanger, x = 0 and x = L

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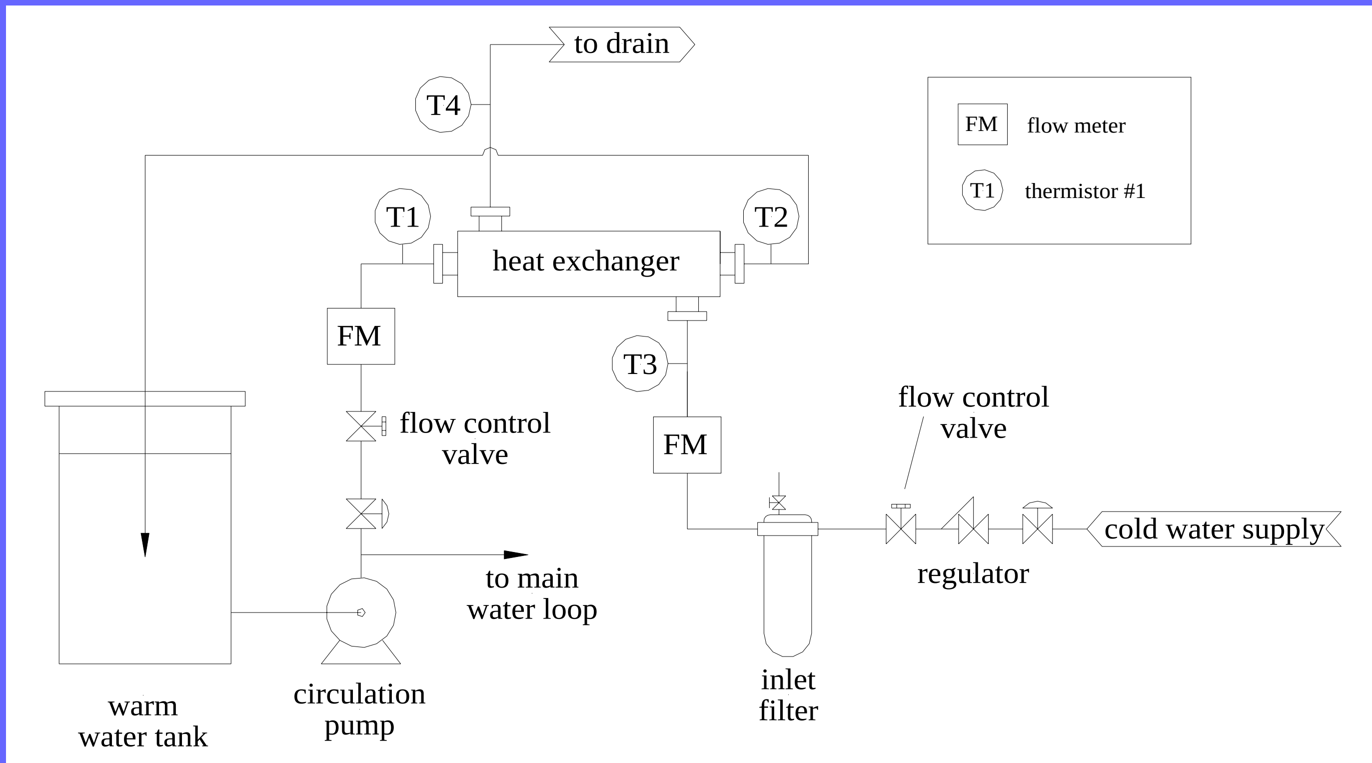
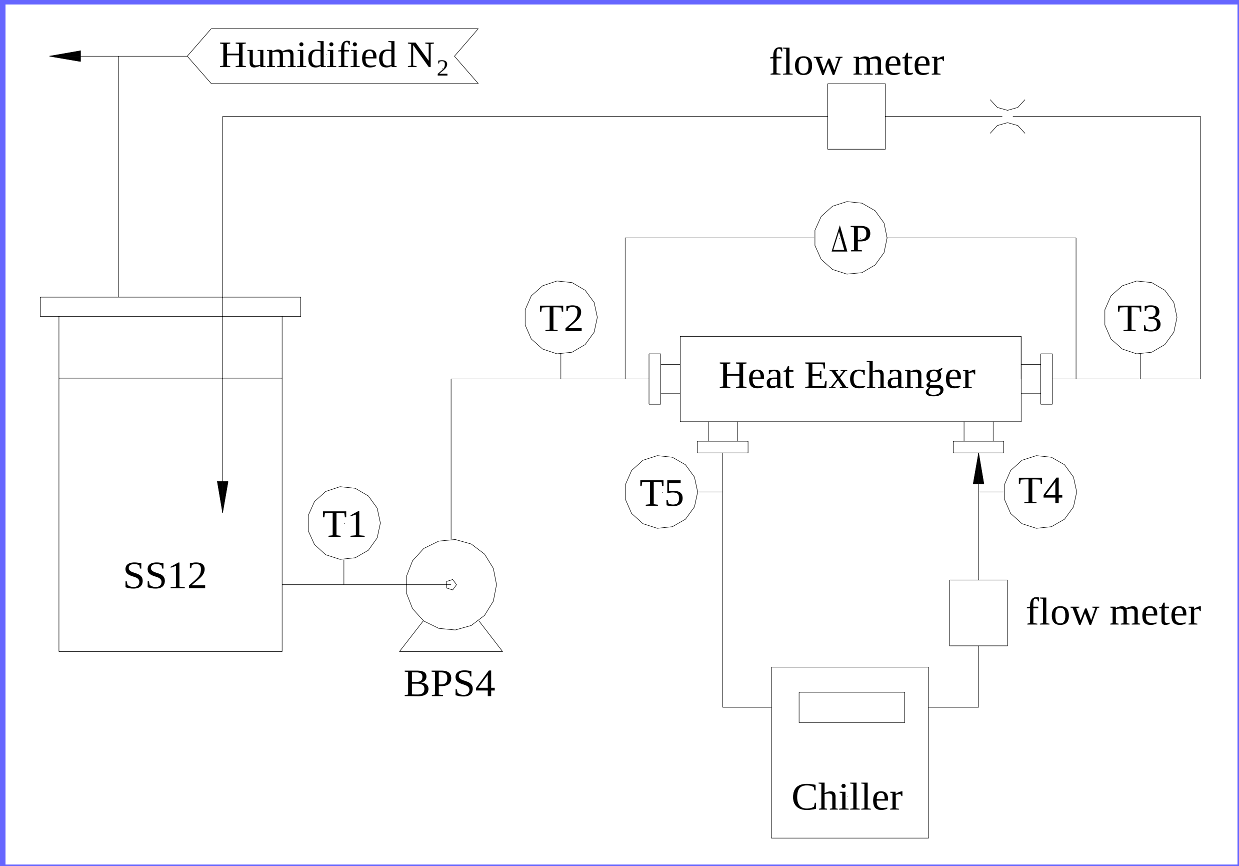
Schematic of heat transfer coefficient test system



Experiments performed in slurry

- Measurement of the effect of the heat exchanger on the slurry particle size distribution (PSD) of Cabot Semi-Sperse® 12 (SS-12).
  - PHX08U (U-line long)
    - 38.5 lpm
    - 10 lpm
  - Stainless steel coil (control test)
    - 38.5 lpm

Slurry test system schematic



Details of tests performed in slurry

- Tests at 38.5 lpm (PHX08U and control test):
  - Test system volume: 50L of SS-12
  - Duration: 5 days (or ~5,700 turnovers)
  - Pump outlet pressure: 34 psig
- Test at 10 lpm (PHX08U test only):
  - Test system volume: 29L of SS-12
  - Duration: 10 days (or ~5,700 turnovers)
  - Pump outlet pressure: 3 psig
- All tests:
  - Tank blanketed with humidified N_2: RH > 90%
  - Slurry temperature: 21 ± 1°C
  - SS-25 was filtered using an Entegris Planargard CMP5 10" filter prior to the test
  - SS-25 was then diluted with ultra pure water as it was added to the test system tank.

Particle size measurement

- "Working" particle size distribution
  - Measured using dynamic light scattering
  - Instrument used – NICOMP 380ZLS (Particle Sizing Systems)
  - All particles in a defined volume illuminated simultaneously
  - Particles are sized by measuring their diffusion coefficient
  - Measures relative concentrations
  - Sensitive to about 1% by volume
- "Large particle tail" size distribution
  - Instrument used:
    - AccuSizer 780 sensor (Particle Sizing Systems)
  - Uses a combination of light scattering and light extinction to size particles ≥ 0.56µm
  - Requires dilution
    - CMP Slurries contain $>10^{14}$ working particles/ml
    - The large particle tail contains $\sim10^{6}$ particles/ml (≥ 0.56µm)

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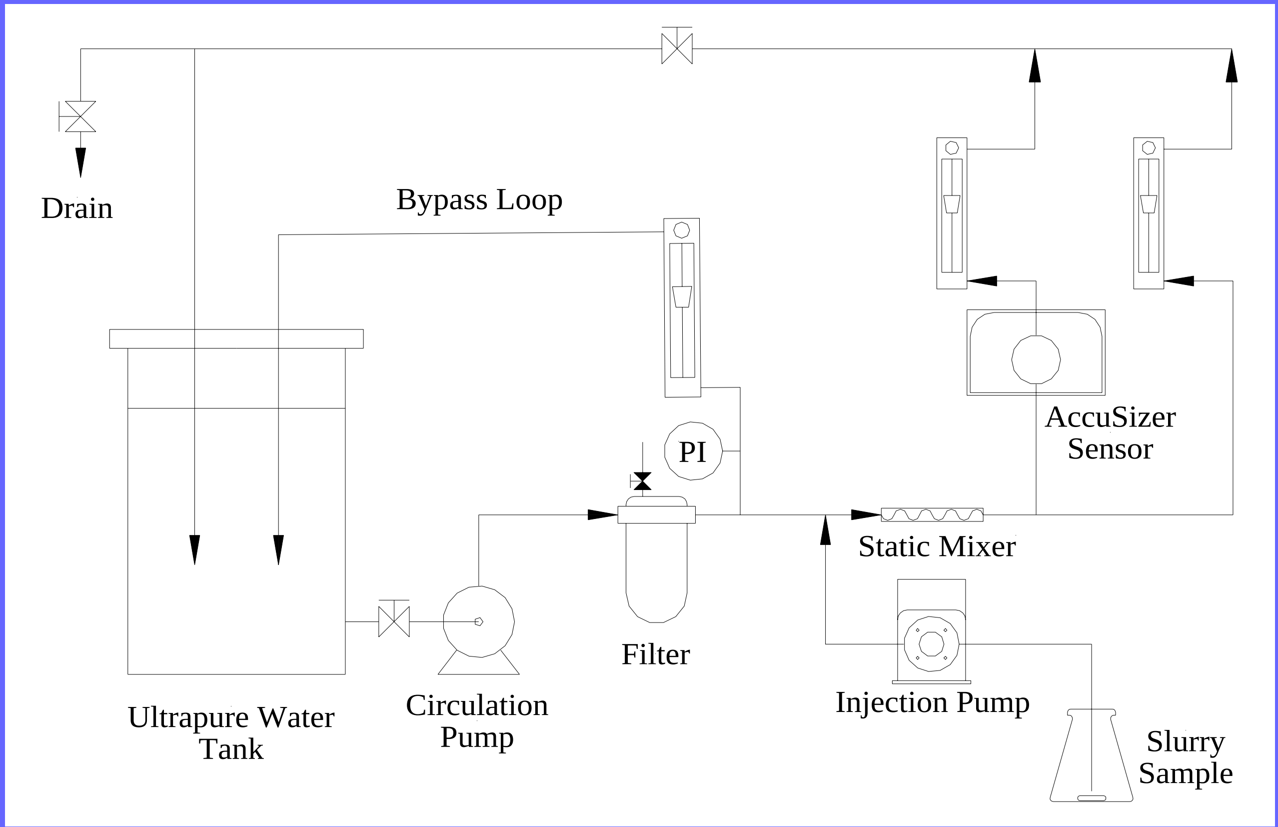
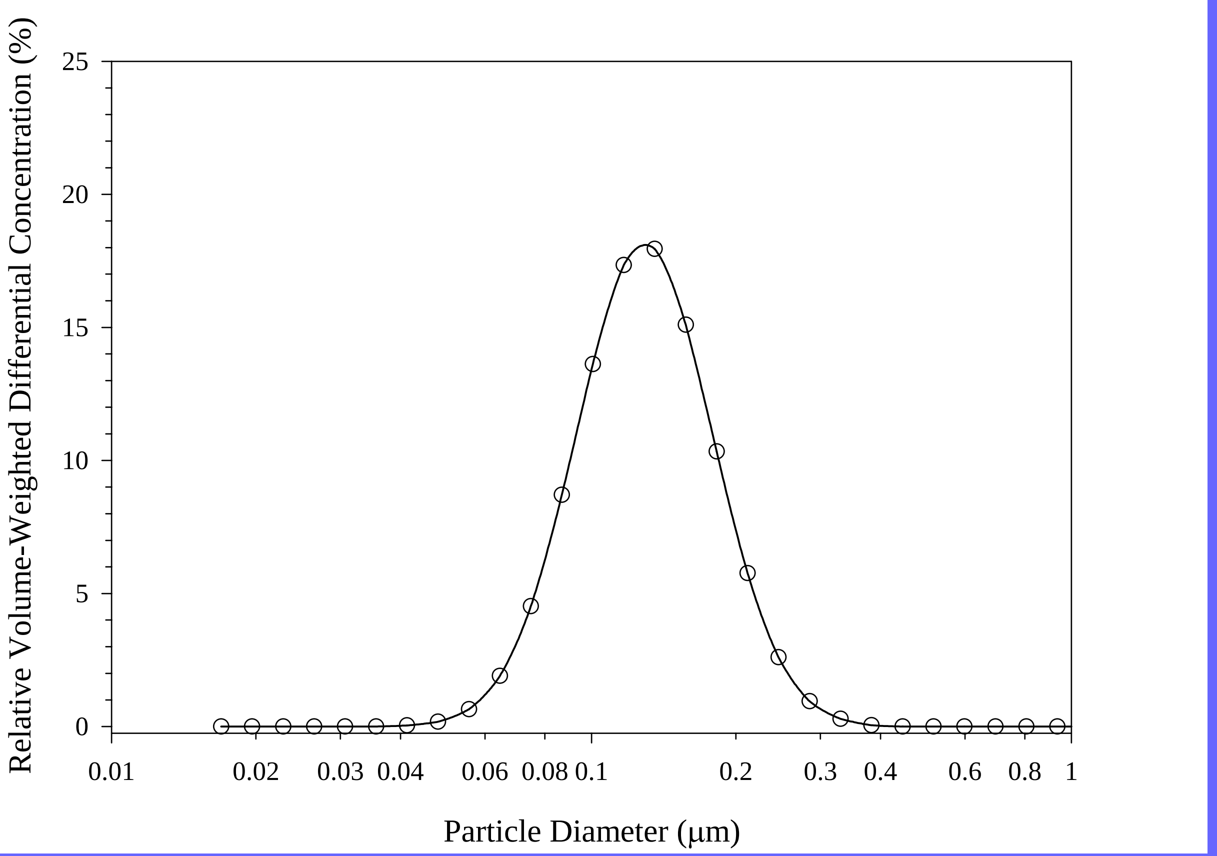
AccuSizer dilution system schematic

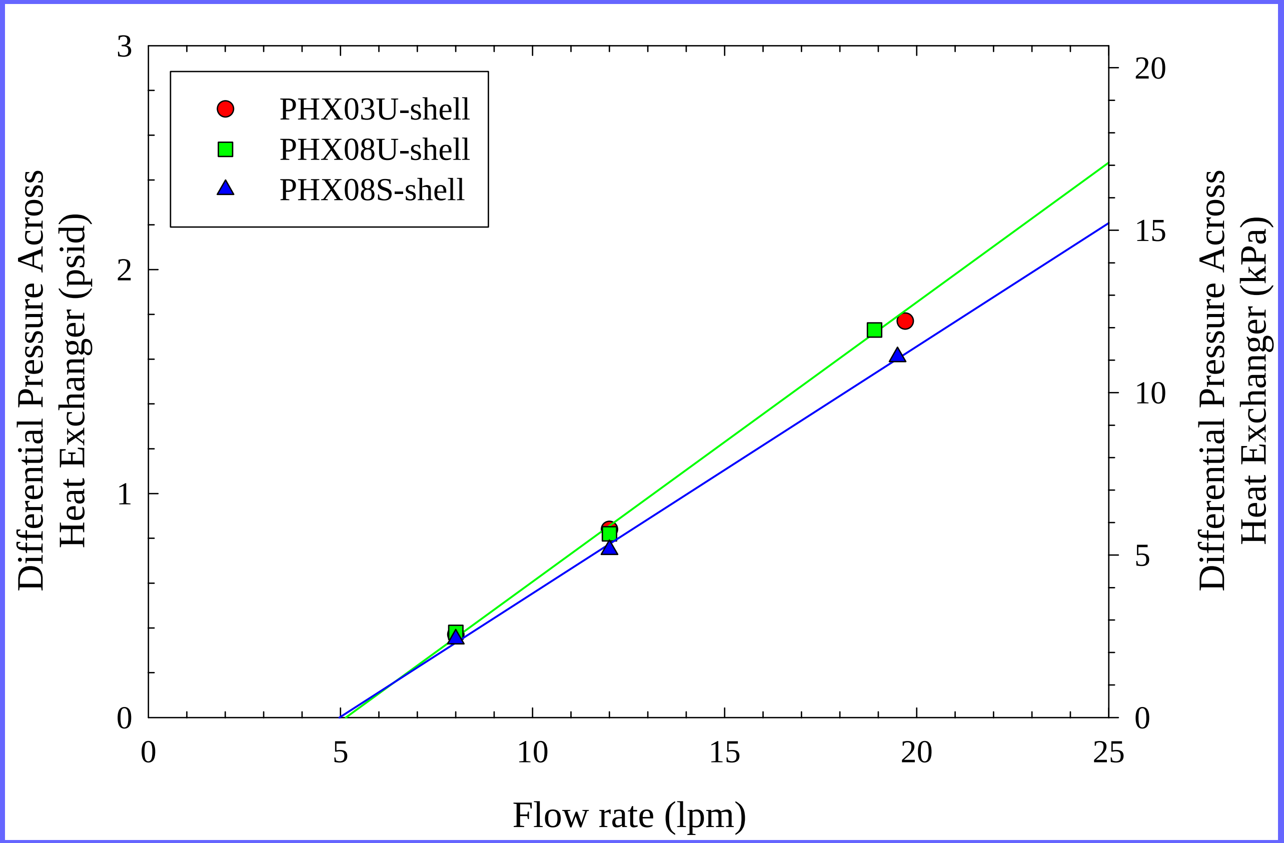


Working particle size distributions (PSDs)

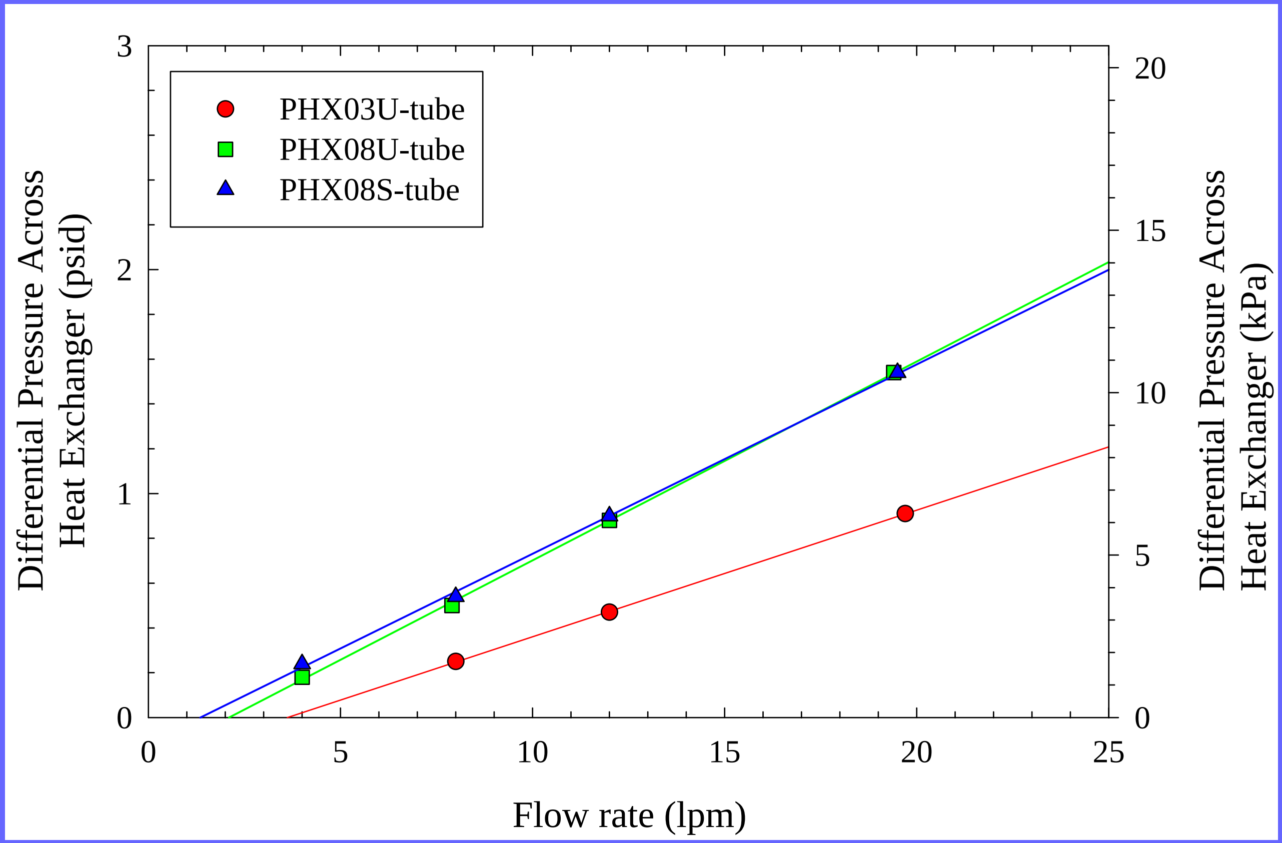


Results

Comparison of Δ P vs. flow rate: shell side



Comparison of Δ P vs. flow rate: tube side



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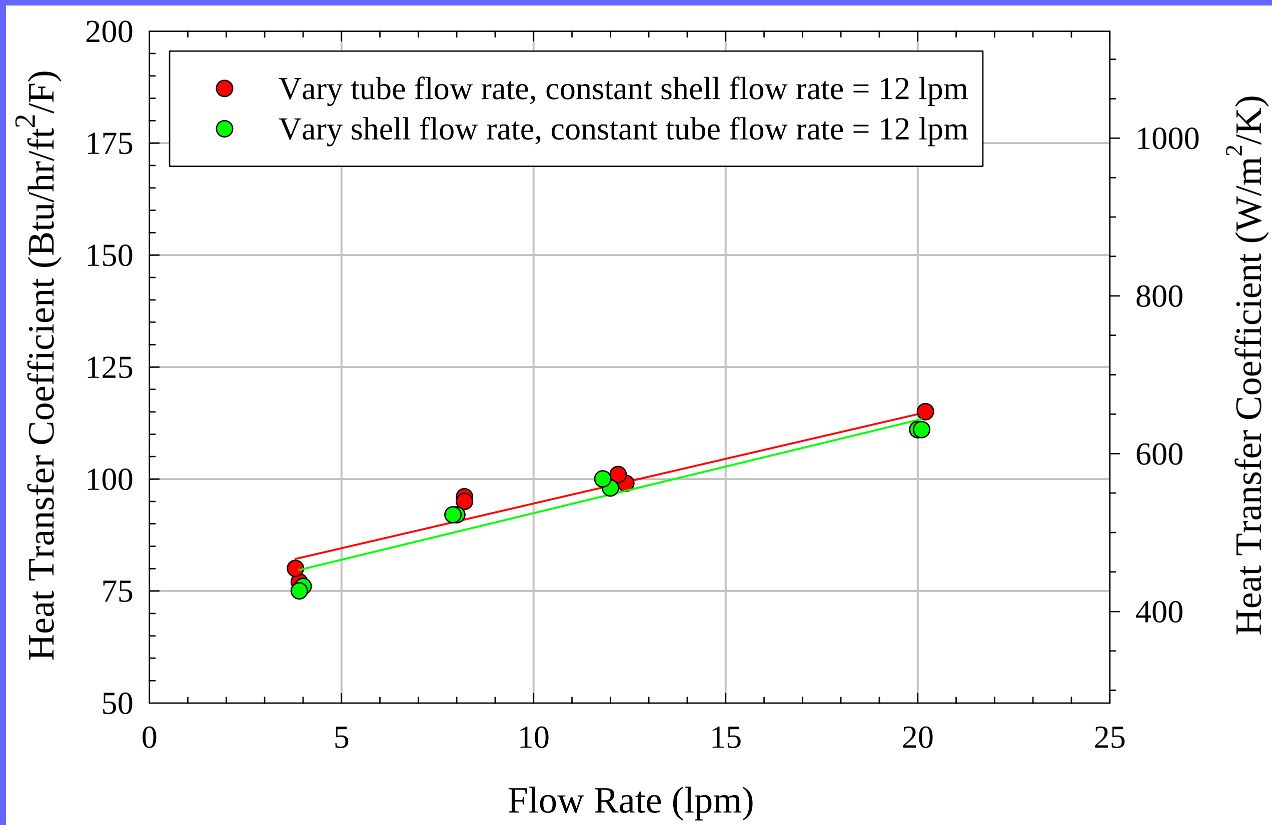
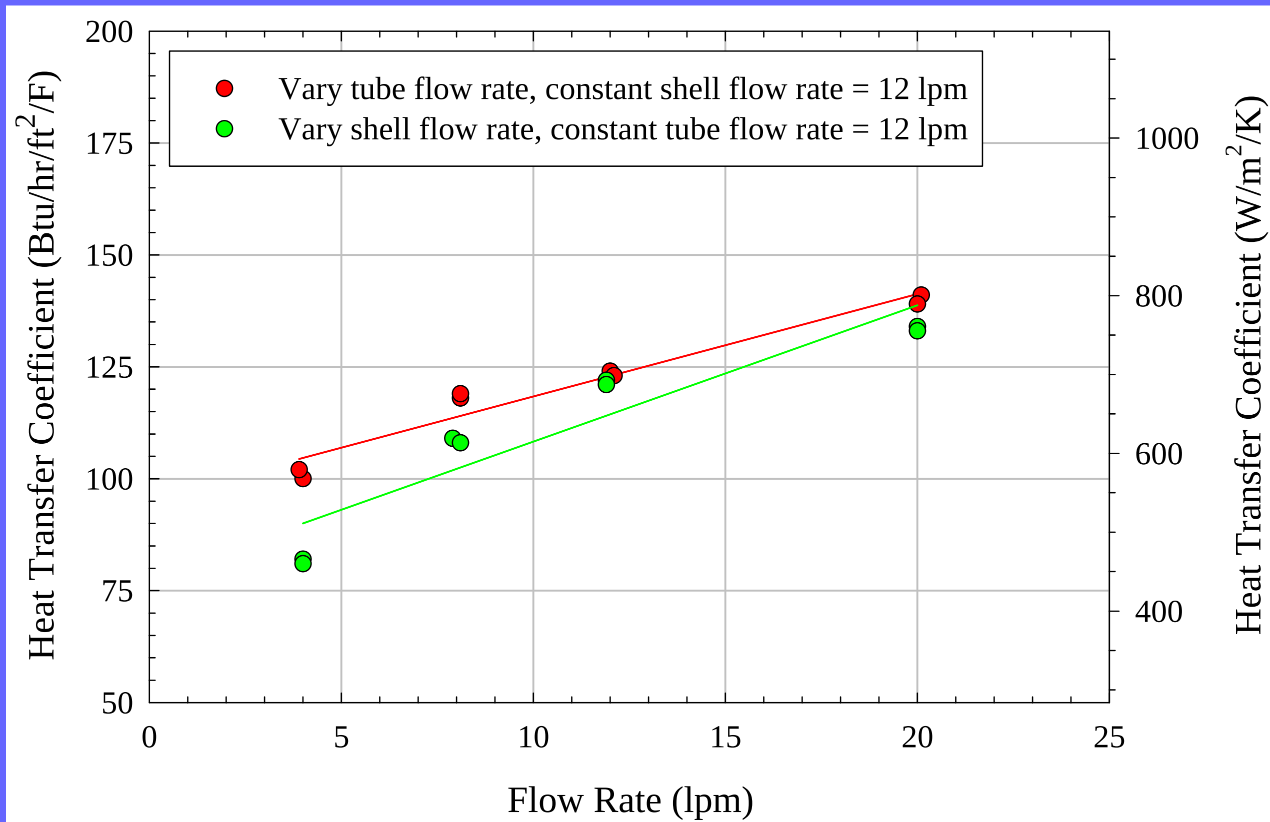
Summary of differential pressure results

- Differential pressure drop versus flow rate were similar for both the PHX08U and PHX08S configurations.
- The Δ P across tubes for the PHX03U configuration was significantly lower.

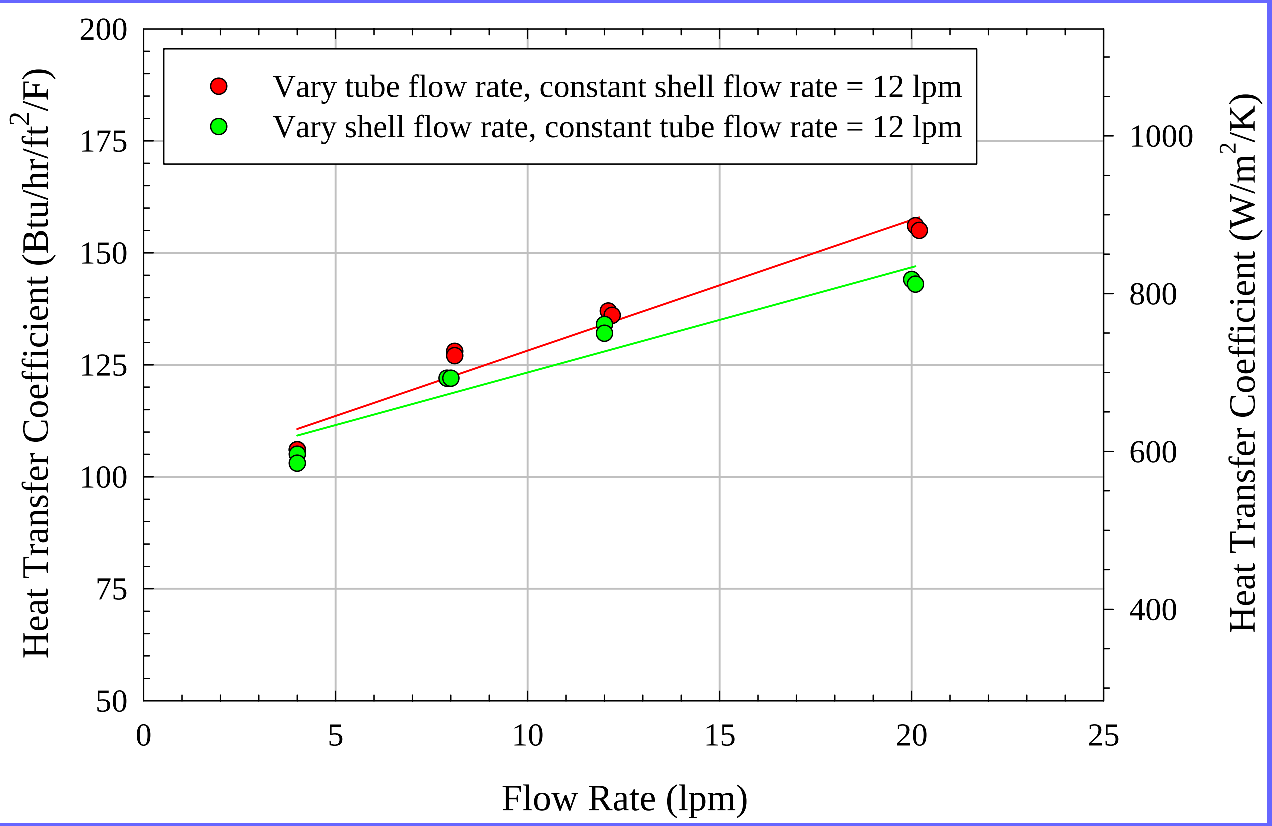
Heat transfer coefficients vs. flow rate: PHX03U



Heat transfer coefficients vs. flow rate: PHX08U



Heat transfer coefficients vs. flow rate: PHX08S



Summary of heat transfer coefficient results

- The S configuration is slightly more efficient than the U configuration.
- The long heat exchangers were more efficient than the short heat exchanger.
- Approach temperatures for these tests were ~10°F, which is a reasonable operating condition.
- Typical heat transfer coefficients in shell and tube heat exchangers ~30-300 Btu/hr/ft^2/°F

Average Heat Transfer Coefficients (Btu/hr/ft^2/°F)			
Configuration	PHX08S	PHX08U	PHX03U
Average of 4 heating and cooling tests	134	124	110
Std. dev.	2.6	2.8	12.1

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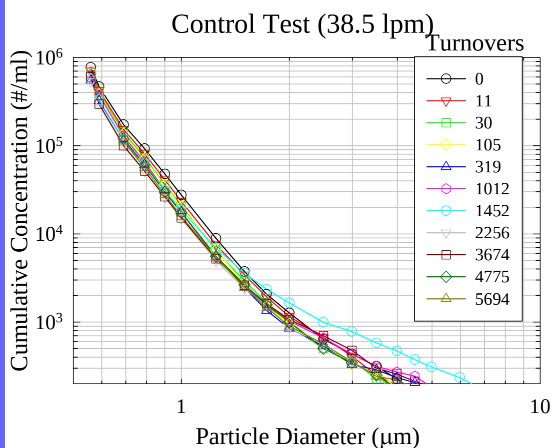
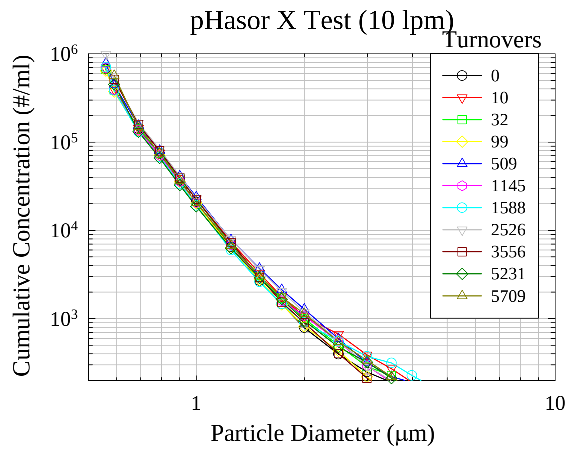
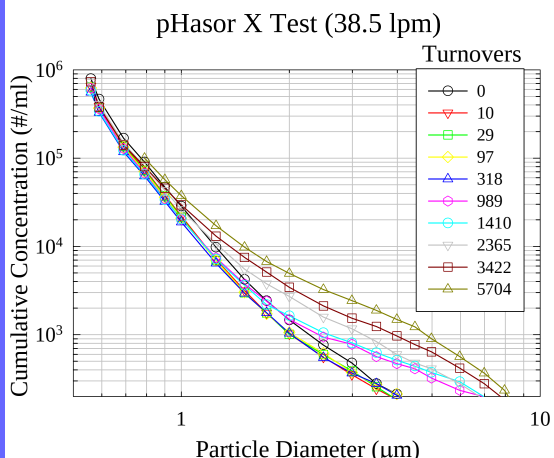
Cumulative PSDs of the large particle tail







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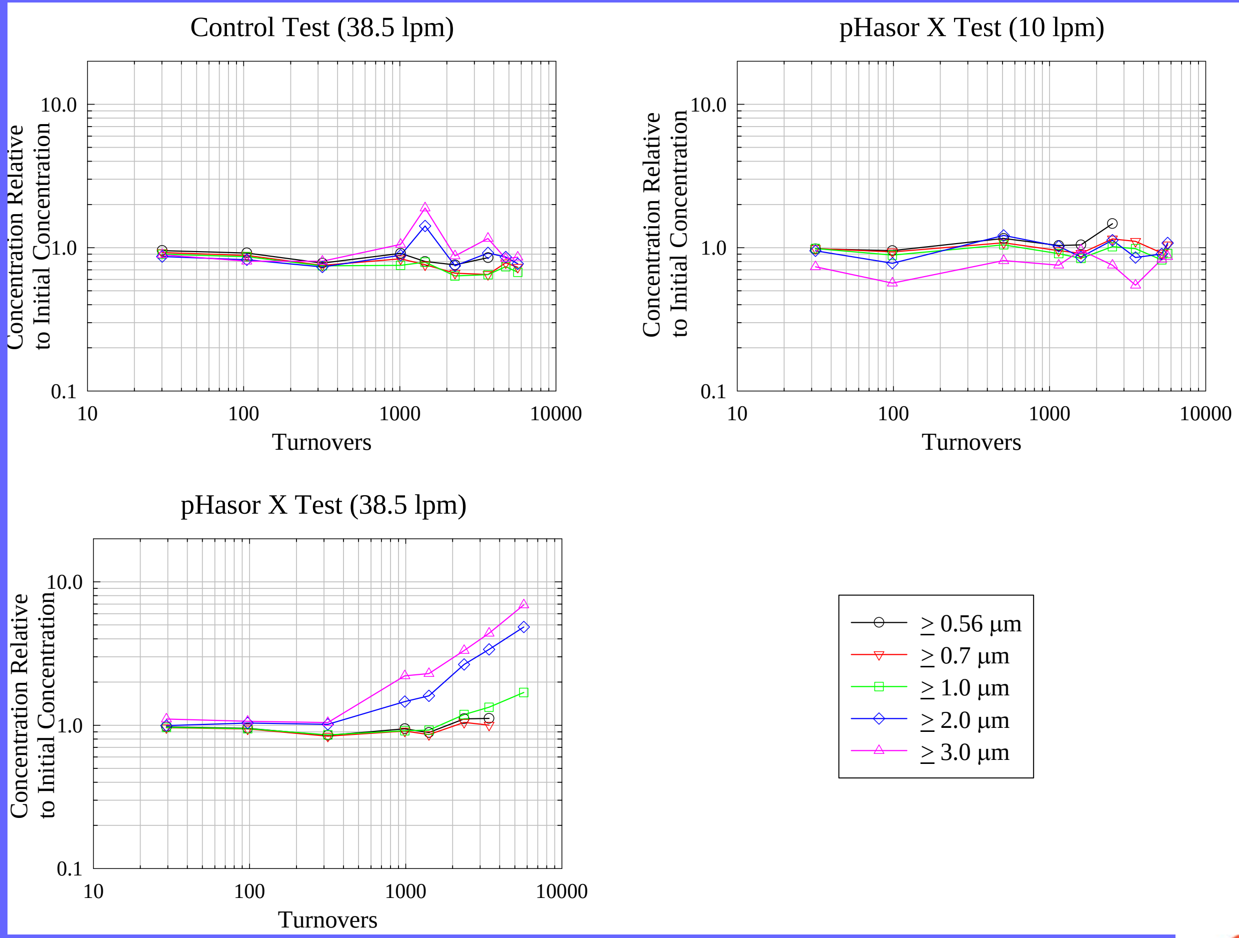
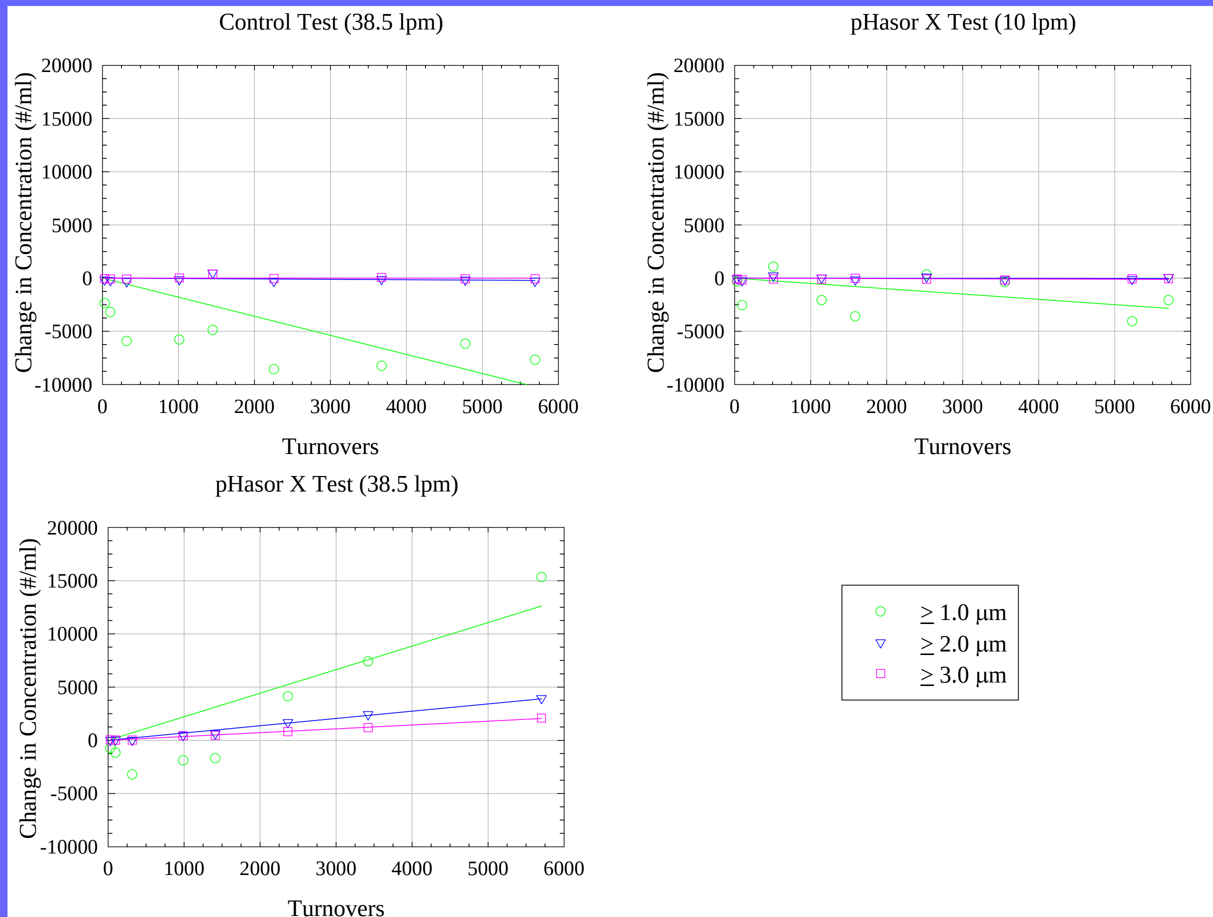
Concentrations relative to initial concentration



Change in concentrations for selected sizes

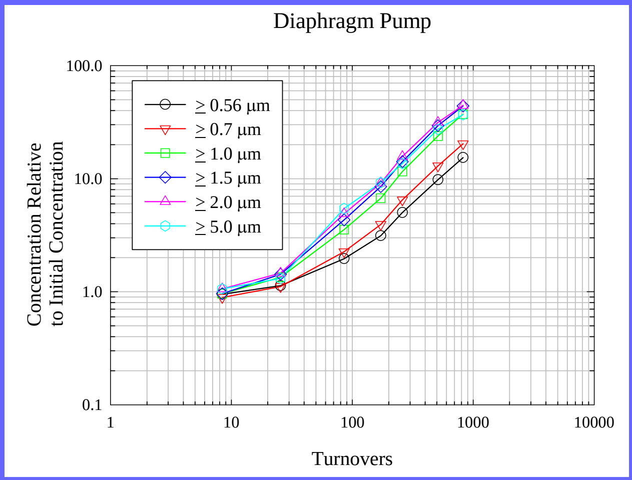


Discussion of large particle test results

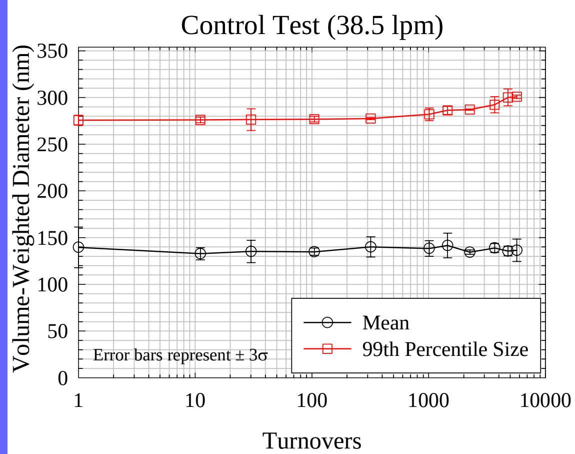
- A slight decrease in the large particle tail was observed during the control test.
- An increase in the concentrations of particles ≥ 1 µm was observed during the heat exchanger test at the higher flow rate.
- Agglomeration at smaller sizes probably occurred as well, but since the concentration of these particles was higher, no increase was apparent.
- Particle concentrations tended to increase roughly linearly with increasing turnovers.

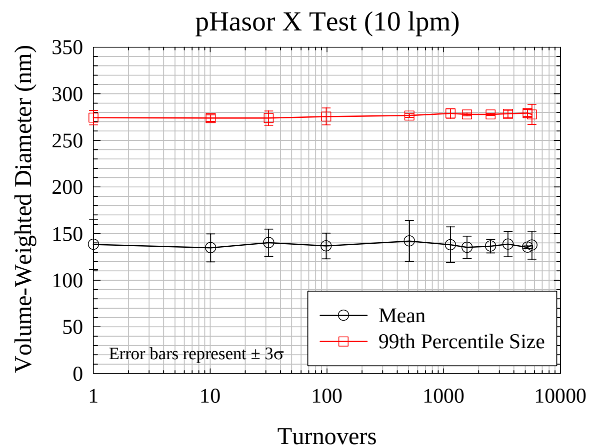
Discussion of large particle test results

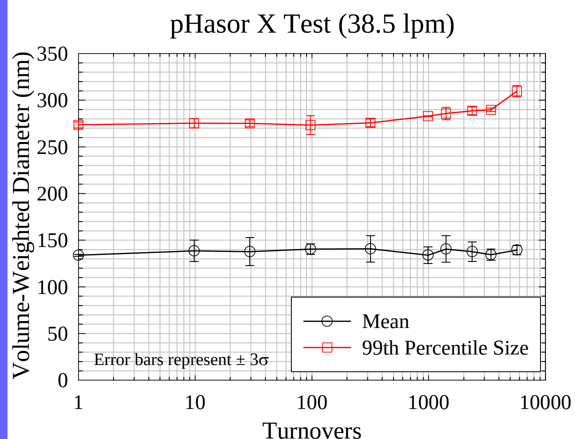
- For particles ≥ 2 µm, the concentration increased by roughly a factor of 5 by the end of the test. This equates to a 0.07% increase in particle concentration ≥ 2 µm per pass through the heat exchanger. In a typical slurry delivery system application, slurry is used with ~100 turnovers, thus only a fairly small increase, ~7%, in concentration would occur.
- This level of increase is dramatically lower than generated by some pumps. (Previous studies have shown up to a 500% increase particle concentrations within 100 turnovers.)



Working particle size measurements







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Discussion of working particle results

- No significant change in the mean or 99th percentile size was observed due to the presence of the heat exchanger.
- A small increase (25-35 nm) in the 99th percentile size was observed during the test at the high flow rate. However, this increase was also observed during the control test, thus it may be attributed to the test system rather than the heat exchanger.

Summary of slurry test results

- No indication of clogging or settling of slurry in the heat exchanger during these tests.
- The heat exchanger was capable of efficiently removing heat so that a constant temperature could be maintained.
- No significant change in the mean or 99th percentile size was observed due to the presence of the heat exchanger.
- Minimal change in the large particle tail was observed during the control test and heat exchanger test at 10 lpm.
- During the heat exchanger test at higher flow, an increase in particle concentrations were observed for particles $\geq 1\ \mu m$ in size.
- Since slurry is typically used within 100 turnovers in a typical delivery system, only a small (~7%) increase in particle concentrations $\geq 2\ \mu m$ would occur.
- This level of increase, although significant, is dramatically lower than that generated by some pump systems.