COMPUTATIONAL FLOW MODEL OF WESTFALL'S 2900 MIXER TO BE USED BY CNRL FOR BITUMEN VISCOSITY CONTROL

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By

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INTRODUCTION

Alden Research Laboratory Inc. (Alden) was contracted by Westfall Manufacturing Inc. (Westfall) to evaluate the performance of a 2800 and 2900 mixer that is intended to be used for bitumen blending for viscosity control. The objective of this mixer is to achieve a low coefficient of variation (CoV) of the injected condensate and butane, and resultant viscosity within a relatively short distance downstream, while staying below the maximum pressure loss requirement (10-psi @ 750-m^3/h). The goal is that the viscosity probe downstream of the condensate and butane injection ports gives an accurate indication of the fluid viscosity – if the true viscosity is higher than the indicated value, CNRL will be outside their pumping requirements. If the true viscosity is lower than the indicated value, CNRL will be unnecessarily using extra condensate. Either alternative is undesirable, so good mixing of the fluids is critical. This report discusses the mixing downstream of the 0.7-Beta 2800 mixer and 2900 mixer at a range of expected flow rates.

COMPUTATIONAL MODEL DESCRIPTION

The model geometry was developed using the commercially available three-dimensional CAD and mesh generation software, GAMBIT V2.4.6. The computational domain generated for the model consisted of 1.5 million cells.

Numerical simulations were performed using the CFD software package FLUENT 13.1, a state-of-the-art, finite volume-based fluid flow simulation package including program modules for boundary condition specification, problem setup, and solution phases of a flow analysis. Advanced turbulence modeling techniques, improved solution convergence rates and special techniques for simulating species transport makes FLUENT particularly well suited for this study.

Alden used FLUENT to calculate the full-scale, three-dimensional, incompressible, laminar and turbulent flow through the pipe and flow conditioner. A two-equation realizable k-ω SST model with Low-Re effects was used to simulate the turbulence, since it has been shown to accurately simulate laminar/turbulent transition, which is critical in this application. Detailed descriptions of the physical models employed in each of the Fluent modules are available from Ansys/Fluent, the developer of Fluent V13.1.

MIXER OPERATING CONDITIONS

Both the 2800 mixer with a 0.7-Beta and the 2900 mixer were evaluated at full scale. Both mixer configurations were evaluated with a 16" pipe inlet and outlet to match the existing pipeline, though the 2900 mixer was evaluated in a 12" pipe size with a reduction and expansion from and to the 16" pipe included in the model. The no-slip condition was applied to all pipe walls, with wall roughness set to 0.00015-ft, which is typical for steel pipe.

The model's inlet boundary condition was placed 6'-8" (5 pipe diameters) upstream of the mixer (the downstream end of the 2900 mixer), and the outlet boundary condition was placed 26'-8" (20 pipe diameters) downstream of the mixer (Figure 1).

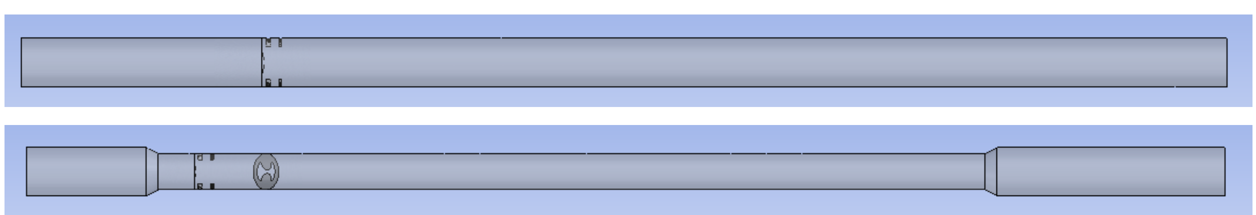


Figure 1 - 2800 Mixer (top) and 2900 Mixer at 50% Open Position (bottom) Model Domains

In the 2900 Mixer, the 12" pipe section extended 20'-0" (20 pipe diameters) downstream of the mixer before it expanded up to the 16" pipe again.

The Bitumen flow rate was set at the model inlet at three flow rates covering the expected flow range: 350-m^3/h (minimum), 650-m^3/h, and 750-m^3/h (maximum without booster pump). Butane was injected at a fixed volumetric flow rate corresponding to 2.5% of the Bitumen flow rate through two opposed 1-inch schedule-40 pipes that extended into the main pipe 1/6 of the pipe inner diameter, and placed 6" downstream of the mixer. Condensate was injected at a flow rate of 5% of the Bitumen flow rate to achieve the desired mixed viscosity through tow opposed 1-1/4" schedule-40 pipes that also extend into the main pipe 1/6 of the pipe inner diameter, and placed 2" downstream of the mixer (Figure 2).

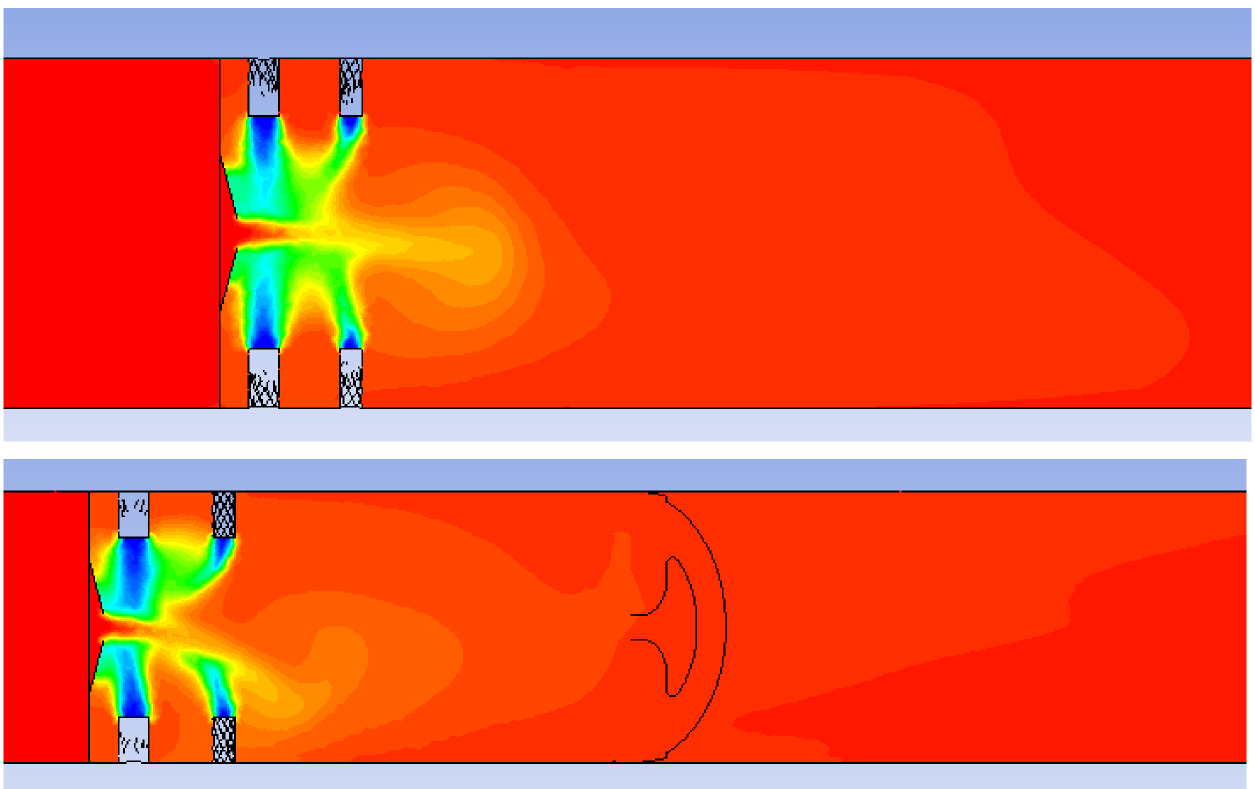


Figure 2 - Condensate and Butane Injection Pipes in 16" 2800 Mixer (top) and 12" 2900 Mixer at 50% Open Position (bottom)

The bitumen, condensate, and butane were treated as fully miscible fluids with all mixture properties taken as the mass weighted average of the individual components (most notably viscosity). Physical properties and flow rates were provided by CNRL. The resulting properties and flow rates for the full flow condition (750-m^3/h) are presented in Table 1.

Table 1 - Physical Properties and Flows at 750-m^3/h

Quantity	Bitumen	Condensate	Butane	Total
Volume Fraction (%)	100%	5.0%	2.5%	107.5%
Volume Flow (m3/h)	750.0	37.5	18.8	806.3
Mass Flow (kg/s)	192.71	7.71	2.73	203.15
Density (kg/m3)	925	740	525	907.1
Density (lbm/ft3)	57.9	46.3	32.8	56.8
Viscosity (cSt)	380	2.0	1.0	353.6
Viscosity (m2/s)	0.00038	0.0000020	0.0000010	0.00035
Viscosity (kg/m-s)	0.3515	0.0015	0.0005	0.3271
Pipe Diameter (in)	16	1.38	1	16
Pipe Diameter (m)	0.406	0.035	0.025	0.406
Pipe Area (m2)	0.12970	0.00096	0.00051	0.12970
Velocity (m/s)	1.61	5.40	5.14	1.73
Velocity (ft/s)	5.27	17.71	16.86	5.67

While the 2800 mixer is captured between a pipe flange and fixed for all flow rates, the 2900 mixer has a fixed upstream mixer (beta = 0.9) and a rotating downstream mixer (beta = 0.7). The three flow rates tested were chose to evaluate the performance of the 2900 mixer with its downstream mixer at 0° (0% open), 45° (50% open), and 90° (100% open).

RESULTS AND DISCUSSION

The goal of the 2800 and 2900 mixers is to achieve a uniform concentration of the injected material within a short downstream distance while meeting the maximum pressure loss criteria. The 2900 mixer is particularly well suited in this regard because its downstream mixer can rotate 90° to significantly reduce the mixer pressure loss at high flows, while optimizing mixing at low flows when the system has reserve pressure to contribute to mixing.

Tabulated results of flow rates, pressure loss values, and outlet viscosity (average, minimum, and maximum) are presented in Table 2.

Table 2 - Tabulated Results of Flows, Pressures, and Viscosities

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Pipe Diameter (in)	16	16	16	12	12	12
Mixer Type	2800	2800	2800	2900	2900	2900
Mixer Beta Ratio	0.7	0.7	0.7	0.9 / 0.7	0.9 / 0.9	0.9 / 0.7
Bitumen Inlet Flow Rate (m3/h)	350	650	750	350	650	750
Butane Flow Rate (m3/h)	8.75	16.25	18.75	8.75	16.25	18.75
Condensate Flow Rate (m3/h)	17.5	32.5	37.5	17.5	32.5	37.5
Inlet Velocity (ft/s)	2.46	4.57	5.27	4.37	8.12	9.37
Downstream Mixer Position (% open)	-	-	-	0%	50%	100%
Pressure Loss (psi)	1.2	4.1	5.4	5.2	8.5	9.3
k-Value of Pipe Section	31.78	31.17	31.14	43.57	20.53	16.97
Viscosity 26'-8" Downstream of Mixer						
Average Viscosity (cSt)	367	367	367	367	367	367
Minimum Viscosity	366	366	367	367	367	367
Maximum Viscosity	374	371	370	368	368	368

The mixer pressure loss was measured from the model inlet to the model outlet, so it included the 33’-4” length of pipe as well, as well as the contraction and expansion in the case of the 2900 mixer. Though the k-value of each mixer configuration is presented, this value is misleading as k-values are intended for turbulent flow where losses are proportional to the velocity squared.

Due to the large viscosity and predominantly laminar flow in the pipeline, there are significant viscous losses, which are proportional to the velocity, and do not scale well using a k-value.

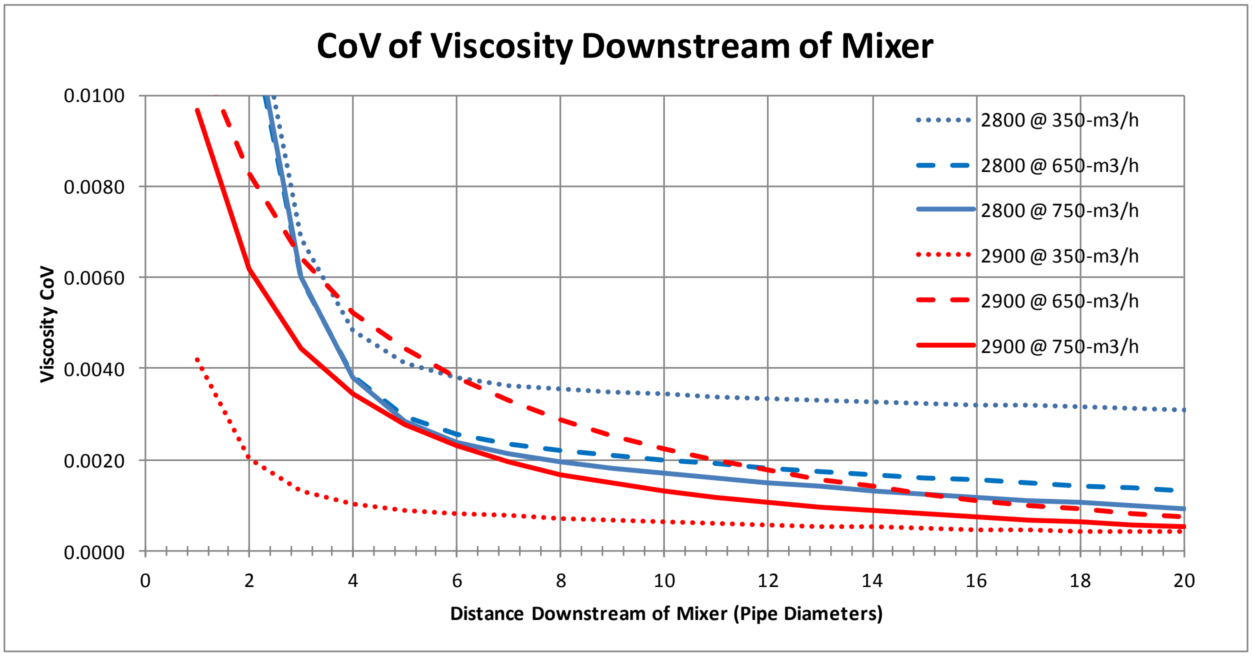
The 0.7-beta 2800 mixer installed in the 16” pipe yields a significantly lower pressure loss than the 2900 mixer installed in the 12” pipe at all flow rates, and at the maximum flow rate, the pressure loss is only 5.4-psi, significantly lower than the maximum allowable pressure loss of 10-psi. This indicates that the 2800 mixer could be placed in a smaller pipe diameter like the 2900 mixer was, and it would still be within the specified pressure limits while providing better mixing than presented here.

The minimum and maximum viscosity 26’-8” downstream of the mixer give a good indication of how well mixed the components are by the time the flow reaches a point where the viscosity measurement may be. For the 2800 mixer in a 16” pipe the minimum viscosity is near the average viscosity for all flow rates; however the maximum viscosity is significantly higher than average, especially at the lowest flow rate (maximum viscosity = 374-cSt, average viscosity = 367-cSt, a 1% difference). For the 2900 mixer in a 12” pipe, both the minimum and maximum viscosities are within 1-cSt of the average for all flow rates.

It should be noted that the calculated average viscosity with the butane, condensate, and bitumen flows and properties used do not yield an average viscosity of 350-cSt as required of the outlet flow. Unless the resulting viscosity does not vary with the mass-weighted average of the component’s viscosities, higher flows of butane and condensate will be required.

The uniformity of viscosity, butane concentration, and condensate concentration can also be calculated using the coefficient of variation (CoV) (Figure 3, Figure 4, Figure 5). Large CoV values indicate a poorly mixed flow, whereas a CoV=0 indicates a perfectly uniform flow.

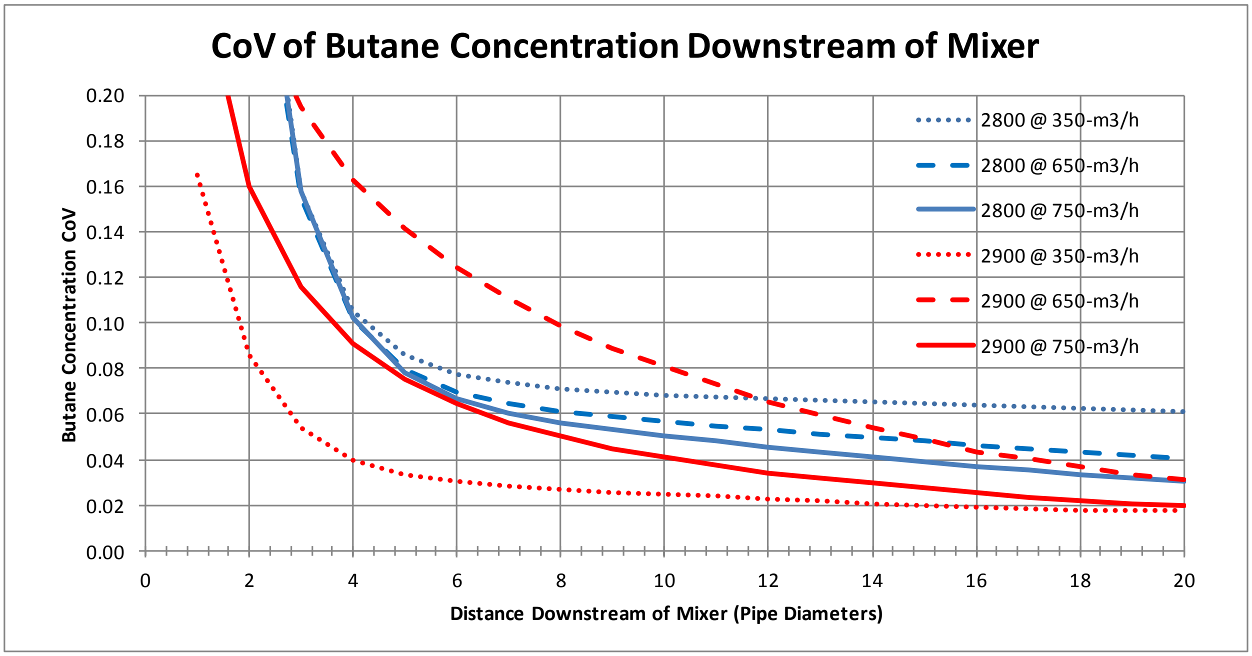
Figure 3 - CoV of Viscosity Downstream of Mixer



CoV of Viscosity

Diameters Downstream of Mixer:	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	0.0317	0.0317	0.0334	0.0042	0.0110	0.0097
2	0.0128	0.0118	0.0121	0.0020	0.0083	0.0062
3	0.0069	0.0060	0.0060	0.0013	0.0064	0.0045
4	0.0048	0.0038	0.0038	0.0010	0.0052	0.0034
5	0.0041	0.0029	0.0028	0.0009	0.0044	0.0028
6	0.0038	0.0025	0.0024	0.0008	0.0038	0.0023
7	0.0036	0.0023	0.0021	0.0008	0.0033	0.0019
8	0.0035	0.0022	0.0020	0.0007	0.0029	0.0017
9	0.0035	0.0021	0.0018	0.0007	0.0025	0.0015
10	0.0034	0.0020	0.0017	0.0006	0.0023	0.0013
11	0.0034	0.0019	0.0016	0.0006	0.0020	0.0012
12	0.0033	0.0018	0.0015	0.0006	0.0018	0.0011
13	0.0033	0.0017	0.0014	0.0005	0.0016	0.0010
14	0.0033	0.0017	0.0013	0.0005	0.0014	0.0009
15	0.0032	0.0016	0.0012	0.0005	0.0012	0.0008
16	0.0032	0.0015	0.0012	0.0005	0.0011	0.0007
17	0.0032	0.0015	0.0011	0.0004	0.0010	0.0007
18	0.0031	0.0014	0.0010	0.0004	0.0009	0.0006
19	0.0031	0.0014	0.0010	0.0004	0.0008	0.0006
20	0.0031	0.0013	0.0009	0.0004	0.0007	0.0005

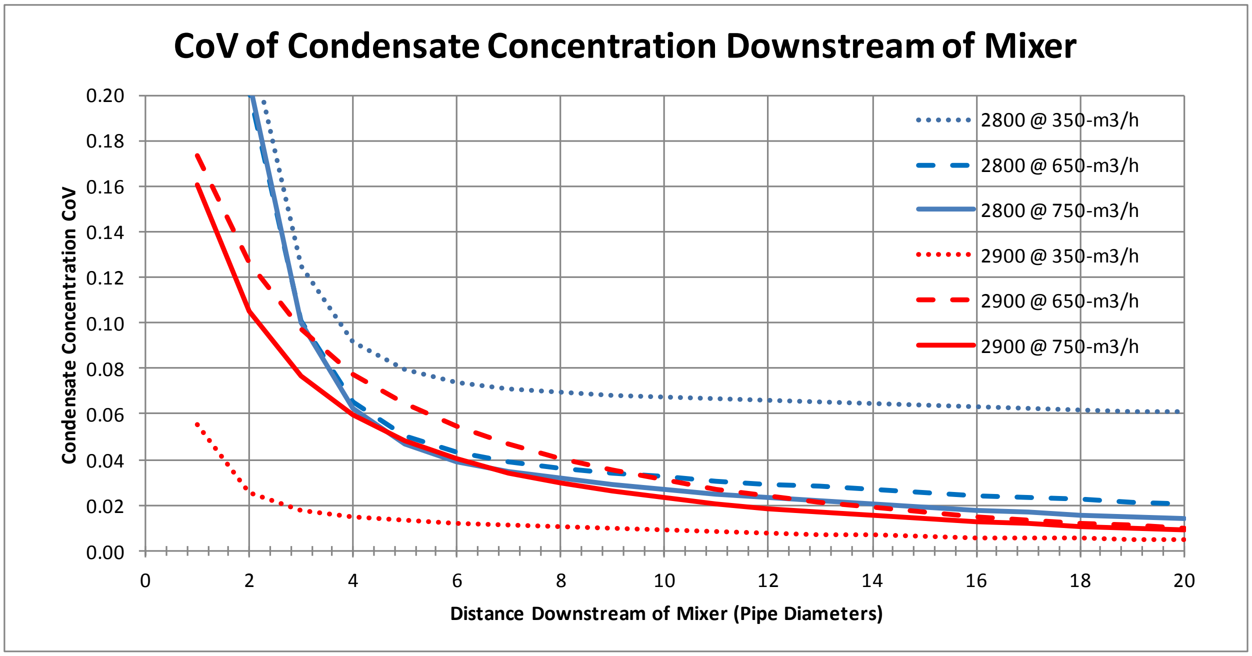
Figure 4 - CoV of Butane Concentration Downstream of Mixer



CoV of Butane Concentration

Diameters Downstream of Mixer:	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	0.86	0.82	0.87	0.16	0.31	0.26
2	0.32	0.30	0.31	0.09	0.24	0.16
3	0.16	0.15	0.16	0.05	0.19	0.12
4	0.10	0.10	0.10	0.04	0.16	0.09
5	0.09	0.08	0.08	0.03	0.14	0.08
6	0.08	0.07	0.07	0.03	0.12	0.06
7	0.07	0.06	0.06	0.03	0.11	0.06
8	0.07	0.06	0.06	0.03	0.10	0.05
9	0.07	0.06	0.05	0.03	0.09	0.05
10	0.07	0.06	0.05	0.02	0.08	0.04
11	0.07	0.05	0.05	0.02	0.07	0.04
12	0.07	0.05	0.05	0.02	0.07	0.03
13	0.07	0.05	0.04	0.02	0.06	0.03
14	0.07	0.05	0.04	0.02	0.05	0.03
15	0.06	0.05	0.04	0.02	0.05	0.03
16	0.06	0.05	0.04	0.02	0.04	0.03
17	0.06	0.04	0.04	0.02	0.04	0.02
18	0.06	0.04	0.03	0.02	0.04	0.02
19	0.06	0.04	0.03	0.02	0.03	0.02
20	0.061	0.040	0.030	0.017	0.03	0.020

Figure 5 - CoV of Condensate Concentration Downstream of Mixer



CoV of Condensate Concentration

Diameters Downstream of Mixer:	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	0.531	0.535	0.559	0.056	0.173	0.161
2	0.225	0.202	0.206	0.026	0.126	0.105
3	0.125	0.101	0.100	0.018	0.097	0.077
4	0.091	0.065	0.063	0.015	0.077	0.060
5	0.079	0.050	0.047	0.013	0.065	0.048
6	0.074	0.043	0.039	0.012	0.055	0.040
7	0.071	0.039	0.035	0.011	0.047	0.034
8	0.070	0.036	0.032	0.010	0.041	0.030
9	0.068	0.034	0.029	0.010	0.035	0.026
10	0.067	0.032	0.027	0.009	0.031	0.023
11	0.067	0.031	0.025	0.008	0.027	0.021
12	0.066	0.029	0.023	0.008	0.024	0.019
13	0.065	0.028	0.022	0.007	0.021	0.017
14	0.064	0.027	0.020	0.007	0.019	0.015
15	0.064	0.026	0.019	0.006	0.017	0.014
16	0.063	0.024	0.018	0.006	0.015	0.013
17	0.063	0.023	0.017	0.006	0.014	0.012
18	0.062	0.022	0.016	0.005	0.012	0.011
19	0.061	0.021	0.015	0.005	0.011	0.010
20	0.061	0.021	0.014	0.005	0.010	0.009

In the fully open and fully closed position, the 2900 mixer provides better uniformity of viscosity at all positions downstream of the mixer. When the downstream mixer is open, this is attributable to the extra two pipe diameters that the upstream mixer has to mix the flow, as well as the smaller pipe size, which increases the shear stress within the flow and promotes better mixing. When the downstream mixer is closed, there are two mixers to mix the flow instead of one, so clearly the mixing will be better. When the downstream mixer is 50% open, there is a region between 3 and 10 diameters downstream of the mixer where the 2800 mixer actually provides better performance, but downstream of this location the additional mixing from the smaller pipe diameter again prevails, and by 20 pipe diameters, the 2900 mixer in the 12-inch pipe has better mixing.

Also of interest with respect to the partially open mixer is that the resistance across the 50% open mixer is not much higher than the fully open mixer. This can be seen in both the k-value (Table 2), and the fact that the intermediate flow (650-m^3/h) is close to the maximum flow (750-m^3/h), and still has a lower pressure loss than at maximum flow with the downstream mixer half-closed. This indicates that:

1. If the downstream mixer is adjusted to maintain a constant pressure loss across the device, the downstream mixer will be closed for a large portion of the flow range, and
2. The change in pressure loss with mixer rotation is much greater when it is first opening than when it is approaching full open, and precision in the actuation and control systems should reflect this.

CONCLUSIONS

Both mixers evaluated provide good mixing, though the 2900 mixer in a 12-inch pipe is clearly the better mixer for the application when compared to the 0.7-Beta 2800 mixer in a 16-inch pipe.

The 2900 mixer in a 12-inch pipe gave a solution with min and max viscosity both within 1-cSt of the average by 26’-8” downstream of the mixer, and the pressure loss for all conditions was less than the maximum value of 10-psi at 750-m^3/h.

The 2900 mixer performed better at low flow (350-m^3/h) with the downstream mixer closed, and at high flow (750-m^3/h) with the downstream mixer fully open than at the intermediate flow (650-m^3/h) with the downstream mixer at 50% open.

The resultant viscosity using the given input viscosities and flow rates, assuming a mass-weighted resultant viscosity (367-cSt), is significantly higher than the required outlet viscosity (350-cSt). Either the resultant viscosity of this mixture is lower than its mass-weighted average, or higher flow rates of condensate and/or butane are needed. The injection pipe sizes for condensate and butane are recommended based on achieving maximum injection velocities greater than 15-ft/s for better mixing. If the flow rates of butane and condensate are increased, the injection pipe sizes can be increased slightly as long as this injection velocity is maintained, or the injection pipe diameter can remain constant at the cost of higher injection pressure loss, but with improved mixing performance. It is recommended that the injection locations of 2” and 6” downstream of the upstream mixer are maintained.

There is a possibility that the maximum flow rate of the system could be increased from 750-m^3/h to 950-m^3/h. If this were to occur, the pressure loss across the mixer would increase to potentially 15-psi. As the whole system would need to install booster pumps to increase the capacity, this extra pressure can be accommodated in the booster pump sizing.

Though the performance of the 16-inch 2800 was not as good as the 12-inch 2900 mixer, the 2800 mixer had significant margin with respect to pressure loss, so its performance could be significantly improved by either reducing the pipe size, or even better, by placing two of these mixers in series. By placing two 2800 mixers in series, the system would gain the benefit of two-stage mixing as seen at low flows in the 2900 mixer, but across the entire flow range. The mixing would likely not be as good at the minimum flow as seen in the 2900 mixer, but mixing would likely be better at intermediate and high flows when it is more critical to have accurate viscosity readings. This would also reduce eliminate the need for a control system.