
Supplementary Material

System Hydrodynamics of a 1 MW_{th} Dual Circulating Fluidized Bed Chemical Looping Gasifier

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Explanation: This supplementary Material Contains the most important boundary conditions for the operating points under consideration. Chapter S1 contains the boundary conditions for the 1 MW_{th} pilot plant, Chapter S2 for the cold flow model.

Supplementary Material S1 – Boundary Conditions of Operating periods from 1 MWth Pilot Plant under Consideration

The boundary conditions for each steady-state operating period under consideration are listed in **Table S1** (K1), **Table S2** (K2), and **Table S3** (K3).

Table S1. Operating conditions for steady-state operating periods under investigation in K1 with corresponding solid samples. K1-BPX (steady-state operating period).

| Variable | Description | BP1 | BP2 | BP3 | BP4 | BP5 | BP6 | BP7 | Unit |
|-------------------------------|---|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 156.1 | 167.5 | 163.4 | 175.4 | 190.3 | 191.5 | 223.2 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 34.7 | 88.4 | 68.2 | 56.6 | 0 | 41.9 | 0 | kg/h |
| T_{AR} | AR max. temperature | 898.6 | 885.2 | 879.3 | 884.8 | 843.6 | 877.2 | 958.6 | °C |
| T_{FR} | FR max. temperature | 812.2 | 820.9 | 821.7 | 821.9 | 756.7 | 772.9 | 858.9 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 21.5 | 32.9 | 44.4 | 39.5 | 29 | 32.8 | 41.7 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -3.1 | -3.1 | -3.1 | -3.1 | -3.1 | -3.1 | -1 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 37.5 | 45.9 | 49.5 | 50.3 | 65.1 | 65.8 | 70.6 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 5.5 | 5.4 | 5.5 | 5.6 | 5.1 | 5.2 | 7.4 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 304.8 | 306 | 301.6 | 297.2 | 249.8 | 253.7 | 237.7 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 953.7 | 952.3 | 952.1 | 953.9 | 932.5 | 921.7 | 1004.8 | kg/h |
| $\dot{m}_{\text{CHS,AR}}$ | Mass flow of propane entering AR | 16.6 | 18.3 | 19.4 | 19.4 | 19.4 | 19.4 | 8.6 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 19.2 (N ₂) | 19.3 (N ₂) | 19.2 (N ₂) | 19.4 (N ₂) | 20.5 (N ₂) | 22 (N ₂) | 16 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 26.7 (N ₂) | 29.2 (N ₂) | 29.9 (N ₂) | 30.8 (N ₂) | 30.4 (N ₂) | 31 (N ₂) | 20.6 (CO ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 13.4 (N ₂) | 15.7 (N ₂) | 16.8 (N ₂) | 16.9 (N ₂) | 18.3 (N ₂) | 18.1 (CO ₂) | 18.4 (N ₂) | Nm ³ /h |
| Solid | Name of Solid Sample from LS1 & | // | // | // | // | // | // | // | - |
| Samples | LS5 | // | // | // | // | // | // | // | - |
| $d_{p,m}$ | Average particle diameter of OC | // | // | // | // | // | // | // | μm |
| Q_p | Particle density of OC | // | // | // | // | // | // | // | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | // | // | // | // | // | // | // | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S1.** Operating conditions for steady-state operating periods under investigation in K1 with corresponding solid samples. K1-BPX (steady-state operating period).

| Variable | Description | BP8 | BP9 | BP10 | BP11 | BP12 | BP13 | BP14 | BP15 | Unit |
|-----------------------------------|---|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 222.8 | 223.6 | 226.4 | 220.8 | 231.8 | 226.4 | 235 | 229.1 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 0 | 33.2 | 35.3 | 24.9 | 46.1 | 53.8 | 0 | 50.9 | kg/h |
| T_{AR} | AR max. temperature | 957.9 | 963.1 | 974.5 | 992.6 | 943.3 | 948 | 919.8 | 911.6 | °C |
| T_{FR} | FR max. temperature | 858.7 | 869 | 892.3 | 908.7 | 864.6 | 881.4 | 839.5 | 833.6 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 37.8 | 45 | 52 | 48.7 | 47.3 | 39.8 | 55.4 | 53.7 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -1 | -1 | -1 | -1 | -1.1 | -1.1 | -0.9 | -0.9 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 69.6 | 61.4 | 68 | 66.4 | 70.6 | 69.3 | 75.9 | 73.4 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 7.8 | 7.2 | 7.6 | 5.8 | 6.8 | 7.2 | 5.1 | 5.2 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 239.1 | 232.1 | 227 | 229.9 | 230.9 | 235.7 | 216.8 | 217.9 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1005.7 | 965.6 | 965.6 | 966.2 | 970.2 | 1000.6 | 969.4 | 971 | kg/h |
| $\dot{m}_{\text{CH}_4,\text{AR}}$ | Mass flow of propane entering AR | 8.6 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 6.8 | 3.6 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 15.9 (N ₂) | 15.7 (N ₂) | 15.1 (N ₂) | 14.9 (N ₂) | 15.6 (N ₂) | 15.2 (N ₂) | 15.7 (N ₂) | 15.6 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 19.6 (CO ₂) | 18.8 (CO ₂) | 19.5 (CO ₂) | 19.1 (CO ₂) | 19.3 (CO ₂) | 16.5 (CO ₂) | 14.9 (CO ₂) | 15.3 (CO ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 20.9 (CO ₂) | 21.8 (CO ₂) | 22 (CO ₂) | 22 (CO ₂) | 22.9 (CO ₂) | 23.7 (CO ₂) | 19.5 (CO ₂) | 18.9 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | // | // | 1-S-42 | // | // | // | // | 1-S-61 | - |
| | | // | // | 1-S-43 | // | // | // | // | 1-S-62 | - |
| $d_{p,m}$ | Average particle diameter of OC | // | // | 130.3 | // | // | // | // | 161.0 | μm |
| ρ_p | Particle density of OC | // | // | 3673.8 | // | // | // | // | 3499.6 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | // | // | 19.9 | // | // | // | // | 16 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S1.** Operating conditions for steady-state operating periods under investigation in K1 with corresponding solid samples. K1-BPX (steady-state operating period).

| Variable | Description | BP16 | BP17 | BP18 | BP19 | BP20 | BP21 | BP22 | BP23 | Unit |
|-----------------------------------|---|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 221.3 | 223.7 | 221.5 | 228.9 | 228.9 | 230.2 | 226.6 | 232.5 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 0 | 1.7 | 0 | 0 | 23.2 | 91.8 | 0 | 13 | kg/h |
| T_{AR} | AR max. temperature | 906.2 | 904 | 903.3 | 902.2 | 893.8 | 884.4 | 883.7 | 882.1 | °C |
| T_{FR} | FR max. temperature | 821.7 | 821.3 | 816 | 814.2 | 808.8 | 806.6 | 800.5 | 792.9 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 44 | 42.3 | 47.2 | 45.2 | 47.6 | 56.5 | 64.4 | 63.8 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -1.1 | -1.1 | -1.1 | -1.1 | -1.1 | -1.1 | -1.2 | -1.2 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 90 | 91 | 77.8 | 74.7 | 74.2 | 73.5 | 65.2 | 63.5 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 7.4 | 6.9 | 7 | 8.1 | 6.4 | 7.3 | 7.2 | 7.1 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 186.5 | 183.7 | 164.7 | 181.8 | 183.8 | 193.8 | 195.8 | 197.3 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 972.8 | 968.2 | 928.2 | 929.3 | 928.2 | 969.3 | 933.1 | 927.2 | kg/h |
| $\dot{m}_{\text{CH}_4,\text{AR}}$ | Mass flow of propane entering AR | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 7.2 | 5.4 | 5.4 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 15 (N ₂) | 15 (N ₂) | 15.2 (N ₂) | 15.3 (N ₂) | 15.2 (N ₂) | 16 (N ₂) | 16 (N ₂) | 16.1 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 14.9 (CO ₂) | 14.8 (CO ₂) | 15.7 (CO ₂) | 15.5 (CO ₂) | 15.8 (CO ₂) | 20.3 (N ₂) | 20.6 (N ₂) | 20.5 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 11.8 (CO ₂) | 11.6 (CO ₂) | 11.6 (CO ₂) | 11.6 (CO ₂) | 12.4 (CO ₂) | 14.7 (CO ₂) | 13.3 (CO ₂) | 12.5 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | 1-S-66 | // | // | // | // | // | // | 1-S-70 | - |
| | | 1-S-65 | // | // | // | // | // | // | 1-S-69 | - |
| $d_{p,m}$ | Average particle diameter of OC | 147.0 | // | // | // | // | // | // | 149.3 | μm |
| ρ_p | Particle density of OC | 4021.1 | // | // | // | // | // | // | 3539.1 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 19.3 | // | // | // | // | // | // | 14.9 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S1.** Operating conditions for steady-state operating periods under investigation in K1 with corresponding solid samples. K1-BPX (steady-state operating period).

| Variable | Description | BP24 | BP25 | BP26 | BP27 | BP28 | BP29 | BP30 | Unit |
|--|---|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 229.8 | 228.9 | 213.7 | 209.5 | 209.6 | 221.9 | 238.8 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 0 | 10.6 | 20.9 | 0 | 0 | 0 | 5.5 | kg/h |
| T_{AR} | AR max. temperature | 882.5 | 868.6 | 844 | 840.7 | 834 | 833 | 797.3 | °C |
| T_{FR} | FR max. temperature | 794.4 | 788.9 | 757.7 | 746 | 730.3 | 725.4 | 722.8 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 64.5 | 64 | 63.4 | 56 | 50.8 | 49 | 74.3 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -1.1 | -1 | -1 | -1 | -1 | -1 | -0.8 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 65.5 | 76.8 | 106.7 | 124.7 | 134.3 | 135.6 | 65 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 7.6 | 7.2 | 7.4 | 7.1 | 7 | 7.1 | 7 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 196.4 | 200.6 | 200.9 | 203 | 203.2 | 204.3 | 251.1 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 927.2 | 944.7 | 952.1 | 953.5 | 956.5 | 957.3 | 960.4 | kg/h |
| $\dot{m}_{\text{CH}_3\text{B}_2\text{AR}}$ | Mass flow of propane entering AR | 5.4 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 16.1 (N ₂) | 16.5 (N ₂) | 16.7 (N ₂) | 16.7 (N ₂) | 16.8 (N ₂) | 16.9 (N ₂) | 17.7 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 20.1 (N ₂) | 18.9 (N ₂) | 16.1 (CO ₂) | 16.3 (CO ₂) | 16.1 (CO ₂) | 16.4 (CO ₂) | 16.8 (CO ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 12.5 (CO ₂) | 18.4 (CO ₂) | 19.4 (CO ₂) | 19.8 (CO ₂) | 20.1 (CO ₂) | 20.9 (CO ₂) | 21.8 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | 1-S-73 | // | 1-S-75 | 1-S-78 | // | 1-S-85 | 1-S-87 | - |
| | | 1-S-74 | // | 1-S-76 | 1-S-79 | // | 1-S-84 | 1-S-86 | - |
| $d_{p,m}$ | Average particle diameter of OC | 134.4 | // | 129.5 | 154.8 | // | 141.2 | 128.7 | μm |
| ρ_p | Particle density of OC | 3542.9 | // | 3430.5 | 3716.3 | // | 3941.8 | 3438.0 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 17.3 | // | 14.8 | 13.7 | // | 13.1 | 10.3 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Table S2. Operating conditions for steady-state operating periods under investigation in K2 with corresponding solid samples. K2-BPX (steady-state operating period).

| Variable | Description | BP1 | BP2 | BP3 | BP4 | BP5 | BP6 | BP7 | Unit |
|--|---|-------------------------|-------------------------|-------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 207.4 | 334.3 | 266.4 | 266.1 | 257.7 | 243.7 | 240.5 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 46.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | kg/h |
| T_{AR} | AR max. temperature | 945.3 | 980.5 | 970.8 | 944.8 | 940.7 | 934.3 | 930.9 | °C |
| T_{FR} | FR max. temperature | 800.4 | 861.2 | 855.8 | 819.0 | 813.9 | 800.8 | 788.5 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 67.8 | 63.4 | 58.0 | 40.6 | 38.2 | 41.7 | 47.4 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -2.1 | -2.1 | -2.0 | -1.9 | -1.9 | -2.0 | -2.1 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 63.8 | 64.6 | 67.7 | 110.7 | 102.2 | 90.3 | 69.5 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 5.9 | 4.4 | 5.9 | 6.0 | 5.4 | 6.4 | 5.9 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 251.7 | 239.8 | 241.1 | 259.1 | 260.5 | 261.4 | 259.7 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 791.3 | 985.0 | 1094.5 | 1141.5 | 1143.2 | 1091.0 | 1044.5 | kg/h |
| $\dot{m}_{\text{CH}_3\text{B}_2\text{AR}}$ | Mass flow of propane entering AR | 3.6 | 3.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 14.5 (N ₂) | 13.9 (N ₂) | 14 (N ₂) | 14 (N ₂) | 14 (N ₂) | 14.2 (N ₂) | 14.9 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 15.1 (N ₂) | 14.3 (N ₂) | 14.2 (N ₂) | 14.4 (N ₂) | 14.3 (N ₂) | 14.5 (N ₂) | 14.7 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 14.2 (CO ₂) | 16.2 (CO ₂) | 15.9 (CO ₂) | 16 (CO ₂) | 17.6 (CO ₂) | 18.2 (CO ₂) | 18.2 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | 2-S-24 | 2-S-26 | 2-S-28 | 2-S-31 | 2-S-33 | 2-S-35 | 2-S-38 | - |
| | | 2-S-23 | 2-S-25 | 2-S-27 | 2-S-30 | 2-S-32 | 2-S-34 | 2-S-39 | - |
| $d_{p,m}$ | Average particle diameter of OC | 179.4 | 181.2" | 182.9" | 185.3" | 186.7" | 188.1 | 189.8" | μm |
| ρ_p | Particle density of OC | 3637.6 | 3631.7" | 3626.4" | 3619" | 3614.6" | 3610.2" | 3606.5" | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 25.1 | 28.3 | 30.0 | 36.4 | 33.6 | 24.5 | 22.9 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S2.** Operating conditions for steady-state operating periods under investigation in K2 with corresponding solid samples. K2-BPX (steady-state operating period).

| Variable | Description | BP8 | BP9 | BP10 | BP11 | BP12 | BP13 | BP14 | BP15 | Unit |
|------------------------------------|---|-------------------------|-------------------------|------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 257.0 | 254.5 | 311.8 | 223.6 | 225.9 | 228.8 | 230.3 | 275.2 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | kg/h |
| T_{AR} | AR max. temperature | 936.3 | 938.1 | 924.2 | 935.5 | 946.9 | 959.6 | 964.6 | 963.0 | °C |
| T_{FR} | FR max. temperature | 789.0 | 774.1 | 738.9 | 765.8 | 784.8 | 792.1 | 814.0 | 816.8 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 45.7 | 36.8 | 34.1 | 36.0 | 41.3 | 44.6 | 47.5 | 40.2 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -2.1 | -2.0 | -2.0 | -2.0 | -2.1 | -1.9 | -2.0 | -2.0 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 64.1 | 80.3 | 95.8 | 82.5 | 62.3 | 96.8 | 74.8 | 67.6 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 6.3 | 6.2 | 4.6 | 4.8 | 4.0 | 5.2 | 5.4 | 5.2 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 261.7 | 262.7 | 294.5 | 304.9 | 307.0 | 319.4 | 324.8 | 324.3 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1041.2 | 1044.6 | 1061.2 | 1055.1 | 1048.6 | 1126.3 | 1158.9 | 1189.9 | kg/h |
| $\dot{m}_{\text{CH}_3\text{B,AR}}$ | Mass flow of propane entering AR | 0.9 | 0.9 | 0.9 | 12.6 | 12.6 | 12.6 | 12.6 | 9.0 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 15 (N ₂) | 14.9 (N ₂) | 14.4 (N ₂) | 14.3 (N ₂) | 14.4 (N ₂) | 14.5 (N ₂) | 14.7 (N ₂) | 14.6 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 14.8 (N ₂) | 14.9 (N ₂) | 15.5 (N ₂) | 15.3 (N ₂) | 15 (N ₂) | 14.9 (N ₂) | 14.4 (N ₂) | 14.3 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 18.5 (CO ₂) | 18.7 (CO ₂) | 16 (CO ₂) | 15.2 (CO ₂) | 18.2 (CO ₂) | 26.4 (CO ₂) | 27.4 (CO ₂) | 32.5 (CO ₂) | Nm ³ /h |
| Solid | Name of Solid Sample from LS1 & LS5 | 2-S-40 | 2-S-42 | 2-S-45 | 2-S-47 | 2-S-51 | 2-S-53 | 2-S-54 | 2-S-59 | - |
| Samples | LS5 | 2-S-41 | 2-S-43 | 2-S-44 | 2-S-46 | 2-S-50 | 2-S-52 | 2-S-55 | 2-S-58 | - |
| $d_{p,m}$ | Average particle diameter of OC | 192.2** | 193.8** | 198.8** | 201** | 202.6 | 204.1** | 204.5** | 204.9** | μm |
| ρ_p | Particle density of OC | 3601.3** | 3597.6** | 3586.8** | 3581.9** | 3578.4** | 3557.3** | 3552.6** | 3546** | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 23.9 | 22.5 | 10.4 | 16.5 | 14.6 | 24.2 | 24.1 | 17.9 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S2.** Operating conditions for steady-state operating periods under investigation in K2 with corresponding solid samples. K2-BPX (steady-state operating period).

| Variable | Description | BP16 | BP17 | BP18 | BP19 | BP20 | BP21 | BP22 | BP23 | Unit |
|------------------------------------|---|-------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 298.5 | 281.1 | 250.6 | 284.6 | 306.4 | 274.2 | 315.1 | 313.3 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 0.0 | 0.0 | 58.8 | 0.0 | 0.0 | 0.0 | 53.2 | 0.0 | kg/h |
| T_{AR} | AR max. temperature | 948.7 | 961.2 | 944.4 | 946.3 | 928.6 | 922.4 | 910.1 | 891.2 | °C |
| T_{FR} | FR max. temperature | 796.8 | 812.7 | 834.7 | 839.1 | 818.2 | 803.8 | 790.5 | 800.2 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 41.4 | 50.4 | 72.8 | 64.6 | 58.1 | 52.9 | 48.8 | 54.6 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -2.0 | -2.1 | -2.1 | -2.0 | -2.0 | -1.8 | -2.0 | -2.0 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 60.6 | 55.6 | 47.9 | 48.2 | 56.0 | 58.6 | 59.6 | 62.5 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 28.9 | 6.8 | 5.3 | 7.0 | 5.5 | 5.0 | 5.5 | 6.0 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 298.8 | 288.6 | 310.5 | 292.9 | 294.1 | 296.8 | 297.9 | 294.6 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1207.9 | 1128.0 | 1098.5 | 1098.8 | 1110.7 | 1113.6 | 1112.6 | 1113.5 | kg/h |
| $\dot{m}_{\text{CH}_3\text{B,AR}}$ | Mass flow of propane entering AR | 5.3 | 5.3 | 7.2 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 13.9 (N ₂) | 14.7 (N ₂) | 15.7 (N ₂) | 15.4 (N ₂) | 15.4 (N ₂) | 15.4 (N ₂) | 15.4 (N ₂) | 15.5 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 14.8 (N ₂) | 13.3 (N ₂) | 13.2 (N ₂) | 13.1 (N ₂) | 12.1 (CO ₂) | 13.5 (N ₂) | 12.7 (CO ₂) | 13.8 (CO ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 15.4 (CO ₂) | 12.4 (N ₂) | 15.8 (N ₂) | 15.8 (N ₂) | 16.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | Nm ³ /h |
| Solid | Name of Solid Sample from LS1 & LS5 | 2-S-80 | 2-S-82 | 2-S-92 | 2-S-96 | 2-S-98 | 2-S-100 | 2-S-102 | 2-S-104 | - |
| Samples | LS5 | 2-S-79 | 2-S-81 | 2-S-91 | 2-S-95 | 2-S-97 | 2-S-99 | 2-S-101 | 2-S-103 | - |
| $d_{p,m}$ | Average particle diameter of OC | 211.2** | 215.0 | 186.2** | 182.7 | 185.3** | 186.9** | 189.9** | 192.1 | μm |
| ρ_p | Particle density of OC | 3457.3** | 3403.2 | 3419.9** | 3421.9** | 3424.5** | 3426.2** | 3429.2** | 3431.5 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 20.1 | 20.9 | 19.6 | 20.4 | 20.7 | 17.9 | 18.1 | 15.0 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Cont'd: **Table S2.** Operating conditions for steady-state operating periods under investigation in K2 with corresponding solid samples. K2-BPX (steady-state operating period).

| Variable | Description | BP24 | BP25 | BP26 | BP27 | BP28 | BP29 | BP30 | BP31 | Unit |
|----------|-------------|------|------|------|------|------|------|------|------|------|
|----------|-------------|------|------|------|------|------|------|------|------|------|

| | | | | | | | | | | |
|-----------------------------------|---|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 323.6 | 298.9 | 336.1 | 353.5 | 324.2 | 370.1 | 310.2 | 302.1 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 46.4 | 0.0 | 0.0 | 52.9 | 0.0 | 49.2 | 25.6 | 50.2 | kg/h |
| T_{AR} | AR max. temperature | 878.9 | 869.0 | 869.7 | 874.4 | 885.0 | 878.2 | 872.3 | 859.6 | °C |
| T_{FR} | FR max. temperature | 800.7 | 803.2 | 799.8 | 807.5 | 815.0 | 816.1 | 821.2 | 807.2 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 46.2 | 49.0 | 42.4 | 44.5 | 40.8 | 42.1 | 37.0 | 29.4 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -2.0 | -1.9 | -2.0 | -1.9 | -2.0 | -2.0 | -2.1 | -1.9 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 61.0 | 61.2 | 59.4 | 62.8 | 63.6 | 65.9 | 78.2 | 97.7 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 6.2 | 5.9 | 6.5 | 6.7 | 7.3 | 7.5 | 6.8 | 6.7 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 297.8 | 300.3 | 301.6 | 291.4 | 284.0 | 284.5 | 290.1 | 300.8 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1097.9 | 1098.7 | 1099.2 | 1095.5 | 1095.8 | 1094.6 | 1118.8 | 1123.4 | kg/h |
| $\dot{m}_{\text{CH}_4,\text{AR}}$ | Mass flow of propane entering AR | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 15.9 (N ₂) | 15.8 (N ₂) | 16 (N ₂) | 15.8 (N ₂) | 15.6 (N ₂) | 15.2 (N ₂) | 15 (N ₂) | 15 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 12.5 (CO ₂) | 13.6 (CO ₂) | 13.4 (CO ₂) | 13.4 (CO ₂) | 13.5 (CO ₂) | 12.9 (CO ₂) | 12.2 (CO ₂) | 13.2 (CO ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 17.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | 17.9 (CO ₂) | 8.5 (CO ₂) | 8.5 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | 2-S-106 | 2-S-110 | 2-S-112 | 2-S-114 | 2-S-117 | 2-S-121 | 2-S-126 | 2-S-130 | - |
| | | 2-S-105 | 2-S-109 | 2-S-111 | 2-S-113 | 2-S-118 | 2-S-122 | 2-S-125 | 2-S-129 | - |
| $d_{p,m}$ | Average particle diameter of OC | 188.5" | 186.7" | 183.3 | 179.9" | 174.9" | 169.0 | 169.1" | 169.2" | µm |
| ρ_p | Particle density of OC | 3415.4" | 3407.4" | 3392.3" | 3384.3" | 3372.3" | 3358.2 | 3347.1" | 3342.4" | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 11.9 | 9.1 | 8.6 | 9.6 | 7.7 | 11.3 | 11.6 | 11.2 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas
 // No solid samples available

Cont'd: **Table S2.** Operating conditions for steady-state operating periods under investigation in K2 with corresponding solid samples. K2-BPX (steady-state operating period).

| Variable | Description | BP32 | BP33 | BP34 | BP35 | Unit |
|-----------------------------------|---|-------------------------|-------------------------|-------------------------|------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 300.3 | 316.2 | 314.6 | 346.8 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 40.0 | 0.0 | 41.5 | 35.0 | kg/h |
| T_{AR} | AR max. temperature | 861.5 | 893.9 | 919.9 | 951.1 | °C |
| T_{FR} | FR max. temperature | 808.6 | 829.7 | 848.5 | 853.5 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 29.5 | 25.5 | 22.9 | 20.0 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -1.9 | -2.1 | -2.0 | -1.9 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 75.1 | 85.6 | 95.3 | 84.1 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 6.6 | 5.1 | 5.0 | 5.2 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 303.0 | 252.8 | 223.8 | 200.8 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1121.9 | 1117.6 | 1115.1 | 1116.3 | kg/h |
| $\dot{m}_{\text{CH}_4,\text{AR}}$ | Mass flow of propane entering AR | 0.9 | 0.9 | 0.9 | 0.9 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 15.1 (N ₂) | 14.6 (N ₂) | 14.2 (N ₂) | 13.9 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 13.2 (CO ₂) | 13.2 (CO ₂) | 13.1 (CO ₂) | 11.1 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 8.5 (CO ₂) | 8.7 (N ₂) | 8.7 (CO ₂) | 8.2 (CO ₂) | Nm ³ /h |
| Solid Samples | Name of Solid Sample from LS1 & LS5 | 2-S-132 | 2-S-136 | 2-S-142 | 2-S-145 | - |
| | | 2-S-131 | 2-S-135 | 2-S-141 | 2-S-146 | - |
| $d_{p,m}$ | Average particle diameter of OC | 169.3" | 169.3" | 169.4" | 169.5 | µm |
| ρ_p | Particle density of OC | 3338.5" | 3335.4" | 3332.4" | 3321.9 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 7.7 | 12.1 | 15.3 | 20.3 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas
 // No solid samples available

Table S3. Operating conditions for steady-state operating periods under investigation in K3 with corresponding solid samples. K3-BPX (steady-state operating period).

| Variable | Description | BP9 | BP11 | BP12 | BP14 | BP16 | Unit |
|-----------------------------------|---|-------------------------|-------------------------|-------------------------|-------------------------|------------------------|--------------------|
| $\dot{m}_{\text{Feedstock}}$ | Mass flow of biomass pellets to FR | 398.7 | 281.5 | 349.1 | 285.2 | 273.5 | kg/h |
| $\dot{m}_{\text{Make-Up}}$ | Mass flow of OC to LS1 | 52.7 | 37.9 | 27.8 | 0.0 | 0.0 | kg/h |
| T_{AR} | AR max. temperature | 962.1 | 986.0 | 975.3 | 952.3 | 951.9 | °C |
| T_{FR} | FR max. temperature | 839.1 | 827.8 | 813.1 | 787.8 | 796.2 | °C |
| Δp_{AR} | AR pressure drop (inventory) | 73.6 | 66.2 | 71.6 | 50.8 | 38.9 | mbar |
| $p_{\text{AR,Cyclone}}$ | Pressure downstream of AR cyclone | -2.0 | -2.0 | -2.1 | -2.0 | -2.0 | mbar |
| Δp_{FR} | FR pressure drop (inventory) | 42.9 | 73.0 | 86.3 | 67.6 | 72.8 | mbar |
| $p_{\text{FR,Cyclone}}$ | Pressure downstream of FR cyclone | 5.1 | 4.9 | 4.8 | 4.8 | 5.0 | mbar |
| $\dot{m}_{\text{FM,FR}}$ | Mass flow of FR fluidization (H ₂ O) | 304.0 | 277.0 | 277.2 | 298.2 | 293.0 | kg/h |
| $\dot{m}_{\text{FM,AR}}$ | Mass flow of AR fluidization* | 1140.7 | 1095.6 | 1105.4 | 1108.9 | 1107.4 | kg/h |
| $\dot{m}_{\text{CH}_8,\text{AR}}$ | Mass flow of propane entering AR | 6.4 | 7.9 | 7.9 | 3.4 | 7.9 | kg/h |
| $\dot{m}_{\text{FM,LS1}}$ | Vol. flow of LS1 fluidization | 16.3 (N ₂) | 16.5 (N ₂) | 16.4 (N ₂) | 16.5 (N ₂) | 16.3 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,LS5}}$ | Vol. flow of LS5 fluidization | 13.8 (N ₂) | 13.8 (N ₂) | 14 (N ₂) | 14.3 (N ₂) | 14.2 (N ₂) | Nm ³ /h |
| $\dot{m}_{\text{FM,J-Valve}}$ | Vol. flow of J-Valve fluidization | 12.7 (CO ₂) | 16.6 (CO ₂) | 16.2 (CO ₂) | 16.6 (CO ₂) | 17 (CO ₂) | Nm ³ /h |
| Solid | Name of Solid Sample from LS1 & | 3-S-17 | 3-S-24 | 3-S-28 | 3-S-32 | 3-S-34 | - |
| Samples | LS5 | 3-S-16 | 3-S-23 | 3-S-27 | 3-S-31 | 3-S-33 | - |
| $d_{p,m}$ | Average particle diameter of OC | 169.0 | 169.5 | 171.5 | 188.0 | 203.2 | μm |
| ρ_p | Particle density of OC | 3398.8 | 3435.5** | 3444.0 | 3403.8** | 3377.3 | kg/m ³ |
| ΔX_s | Change in Xs for OC samples | 16.1 | 21.5 | 25.7 | 20.5 | 18.1 | - |

* AR fluidization medium: pure air or mixture of air & recycled flue gas

// No solid samples available

Supplementary Material S2 – Boundary Conditions of Operating periods from cold flow model under Consideration

The boundary conditions for each steady-state operating period under consideration in the CFM are listed in **Table S4** (bronze) and **Table S5** (ilmenite).

Table S4. Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP1 | BP2 | BP3 | BP4 | BP5 | BP6 | BP7 | BP8 | BP9 | BP10 | Unit |
|----------------------|-----------------------------------|------|------|------|-------|-------|------|-------|------|------|------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.59 | 1.63 | 1.73 | 1.91 | 2.11 | 1.95 | 1.98 | 2.16 | 1.56 | 1.61 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 47.3 | 39.3 | 35.5 | 36.5 | 35.4 | 33.8 | 30.0 | 31.1 | 32.1 | 29.0 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.37 | 2.70 | 3.49 | 2.73 | 2.68 | 2.75 | 2.76 | 2.70 | 3.26 | 2.76 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 17.2 | 25.1 | 26.7 | 22.2 | 22.2 | 34.3 | 36.3 | 35.0 | 8.1 | 10.4 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.8 | 0.85 | 1.1 | 0.39 | 0.315 | 0.59 | 0.605 | 0.49 | 0.4 | 0.4 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 66.2 | 69.5 | 72.7 | 103.4 | 115.1 | 88.7 | 89.1 | 99.2 | 81.6 | 74.8 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 9.7 | 10.3 | 12.6 | 20.3 | 25.6 | 18.4 | 18.5 | 25.9 | 6.6 | 6.9 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 21.4 | 22.6 | 31.0 | 22.0 | 21.4 | 26.3 | 27.0 | 24.9 | 14.4 | 14.6 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-11 | BP-12 | BP-13 | BP-14 | BP-15 | BP-16 | BP-17 | BP-18 | BP-19 | BP-20 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.71 | 1.76 | 1.81 | 1.89 | 1.96 | 2.01 | 2.06 | 1.59 | 2.03 | 1.89 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 28.0 | 27.2 | 24.4 | 22.1 | 20.1 | 19.1 | 17.2 | 32.5 | 15.8 | 21.4 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.38 | 3.08 | 3.38 | 3.38 | 3.33 | 3.27 | 3.16 | 3.18 | 2.90 | 3.03 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 12.1 | 15.4 | 16.2 | 18.1 | 21.8 | 24.5 | 30.5 | 8.5 | 30.9 | 21.0 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.52 | 0.52 | 0.7 | 0.75 | 0.89 | 0.89 | 0.96 | 0.45 | 0.81 | 0.81 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 79.0 | 84.4 | 76.4 | 76.5 | 70.9 | 72.9 | 71.1 | 74.6 | 75.4 | 72.2 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 8.8 | 9.2 | 10.7 | 11.5 | 12.8 | 12.9 | 13.9 | 7.2 | 11.7 | 10.7 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 20.0 | 20.1 | 24.0 | 25.2 | 26.0 | 27.0 | 28.5 | 14.9 | 26.0 | 24.2 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-21 | BP-22 | BP-23 | BP-24 | BP-25 | BP-26 | BP-27 | BP-28 | BP-29 | BP-30 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.74 | 1.82 | 2.02 | 1.94 | 1.88 | 1.85 | 1.79 | 2.00 | 1.80 | 1.82 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 27.7 | 24.2 | 18.3 | 20.8 | 21.4 | 21.2 | 23.2 | 17.6 | 22.6 | 19.9 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.14 | 3.14 | 3.17 | 3.21 | 2.92 | 2.73 | 2.91 | 2.92 | 2.85 | 2.49 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 13.2 | 16.9 | 25.9 | 20.8 | 21.4 | 20.2 | 16.2 | 25.3 | 17.1 | 21.1 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.52 | 0.68 | 0.9 | 0.9 | 0.79 | 0.65 | 0.6 | 0.8 | 0.65 | 0.65 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 80.2 | 75.9 | 72.1 | 73.6 | 69.4 | 73.1 | 74.3 | 71.5 | 71.9 | 70.7 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 9.4 | 10.5 | 12.8 | 11.8 | 10.7 | 9.8 | 9.0 | 11.8 | 9.1 | 8.8 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 21.0 | 22.0 | 26.8 | 25.3 | 23.7 | 20.6 | 20.2 | 25.4 | 20.6 | 18.9 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-31 | BP-32 | BP-33 | BP-34 | BP-35 | BP-36 | BP-37 | BP-38 | BP-39 | BP-40 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.67 | 1.98 | 2.04 | 1.62 | 1.71 | 1.83 | 1.82 | 1.87 | 1.88 | 1.87 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 21.3 | 18.0 | 16.9 | 41.7 | 42.2 | 33.7 | 35.3 | 31.4 | 31.5 | 25.5 | mbar |
| $u_{0,FR}$ | FR gas velocity | 2.14 | 2.75 | 2.78 | 3.29 | 3.21 | 3.16 | 3.13 | 3.00 | 3.08 | 2.73 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 16.1 | 25.6 | 31.3 | 13.0 | 18.7 | 26.2 | 30.1 | 33.5 | 31.2 | 21.0 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.4 | 0.7 | 0.9 | 0.5 | 0.68 | 0.8 | 1.03 | 0.9 | 1.08 | 0.58 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 76.0 | 75.6 | 70.7 | 81.7 | 77.8 | 75.9 | 67.5 | 73.9 | 65.5 | 79.4 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 6.6 | 11.0 | 11.7 | 8.4 | 11.4 | 12.1 | 12.6 | 12.3 | 11.9 | 9.8 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 13.4 | 23.9 | 26.3 | 18.9 | 23.2 | 26.9 | 28.1 | 27.4 | 26.7 | 21.6 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-41 | BP-42 | BP-43 | BP-44 | BP-45 | BP-46 | BP-47 | BP-48 | BP-49 | BP-50 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.88 | 2.04 | 1.62 | 1.71 | 1.71 | 1.83 | 1.82 | 1.95 | 1.71 | 1.81 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 27.5 | 21.2 | 31.0 | 31.4 | 24.4 | 25.4 | 20.1 | 20.3 | 27.5 | 23.8 | mbar |
| $u_{0,FR}$ | FR gas velocity | 2.90 | 2.89 | 2.76 | 3.28 | 2.40 | 3.09 | 2.19 | 2.83 | 3.11 | 3.12 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 21.4 | 25.4 | 8.4 | 9.4 | 10.5 | 11.6 | 15.5 | 13.7 | 7.7 | 9.0 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.68 | 0.68 | 0.4 | 0.41 | 0.36 | 0.41 | 0.5 | 0.65 | 0.48 | 0.5 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 76.6 | 79.5 | 79.8 | 85.8 | 86.9 | 86.2 | 74.6 | 69.6 | 73.7 | 73.7 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 10.4 | 11.7 | 6.0 | 7.9 | 6.2 | 8.1 | 6.4 | 8.1 | 6.2 | 6.8 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 24.4 | 24.2 | 13.9 | 17.1 | 13.6 | 18.3 | 15.2 | 18.4 | 13.4 | 15.5 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-51 | BP-52 | BP-53 | BP-54 | BP-55 | BP-56 | BP-57 | BP-58 | BP-59 | BP-60 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.66 | 1.76 | 1.64 | 1.84 | 1.79 | 1.86 | 1.93 | 1.86 | 1.88 | 1.93 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 38.5 | 48.3 | 45.9 | 25.0 | 27.3 | 22.7 | 28.6 | 28.2 | 19.2 | 13.3 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.34 | 2.89 | 3.35 | 2.87 | 2.76 | 2.75 | 3.18 | 3.01 | 3.06 | 3.00 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 9.3 | 23.5 | 12.0 | 22.0 | 19.3 | 22.3 | 28.6 | 24.2 | 23.9 | 24.2 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.5 | 0.7 | 0.5 | 0.58 | 0.6 | 0.6 | 0.7 | 0.58 | 0.65 | 0.65 | NI/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 76.5 | 76.0 | 81.6 | 84.3 | 78.2 | 80.3 | 79.8 | 83.5 | 73.1 | 73.6 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 7.9 | 10.9 | 9.1 | 10.1 | 9.5 | 9.7 | 13.1 | 10.8 | 10.8 | 10.6 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 17.5 | 23.7 | 20.0 | 23.2 | 19.8 | 21.7 | 27.9 | 23.6 | 23.9 | 24.2 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-61 | BP-62 | BP-63 | BP-64 | BP-65 | BP-66 | BP-67 | BP-68 | BP-69 | BP-70 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.67 | 1.68 | 1.66 | 1.88 | 1.90 | 1.84 | 1.96 | 1.71 | 1.81 | 1.79 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 18.1 | 17.9 | 17.4 | 9.8 | 14.0 | 16.4 | 12.4 | 19.5 | 18.8 | 11.4 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.03 | 2.34 | 3.37 | 3.07 | 3.02 | 2.64 | 2.89 | 2.30 | 3.13 | 2.35 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 8.7 | 11.7 | 6.5 | 13.6 | 18.8 | 19.4 | 22.1 | 12.4 | 11.7 | 13.7 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.35 | 0.3 | 0.38 | 0.48 | 0.55 | 0.5 | 0.58 | 0.35 | 0.5 | 0.35 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 81.9 | 86.0 | 81.2 | 80.1 | 79.6 | 78.9 | 80.7 | 85.7 | 78.8 | 88.4 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 6.3 | 6.3 | 6.2 | 8.7 | 9.8 | 8.6 | 10.3 | 6.4 | 8.4 | 6.6 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 14.2 | 14.1 | 14.1 | 19.2 | 21.8 | 18.5 | 21.7 | 13.5 | 17.7 | 14.7 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-71 | BP-72 | BP-73 | BP-74 | BP-75 | BP-76 | BP-77 | BP-78 | BP-79 | BP-80 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 1.79 | 1.64 | 1.73 | 2.00 | 2.01 | 2.35 | 2.35 | 2.34 | 2.02 | 2.36 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 18.3 | 32.3 | 34.5 | 7.1 | 4.6 | 4.6 | 3.3 | 14.7 | 17.0 | 11.8 | mbar |
| $u_{0,FR}$ | FR gas velocity | 2.80 | 2.52 | 2.97 | 2.54 | 2.92 | 2.92 | 3.29 | 3.28 | 3.29 | 3.30 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 11.5 | 26.5 | 31.0 | 9.2 | 5.5 | 10.5 | 6.4 | 18.0 | 19.5 | 23.1 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.4 | 0.8 | 1 | 0.5 | 0.4 | 0.5 | 0.35 | 0.4 | 0.5 | 0.6 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 82.3 | 76.0 | 71.5 | 77.9 | 79.7 | 81.6 | 74.0 | 104.3 | 98.4 | 100.8 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 7.6 | 9.0 | 14.2 | 5.6 | 4.8 | 5.3 | 4.3 | 15.9 | 11.8 | 13.9 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 17.5 | 20.1 | 28.8 | 15.7 | 11.9 | 19.7 | 15.7 | 23.6 | 26.4 | 28.1 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-81 | BP-82 | BP-83 | BP-84 | BP-85 | BP-86 | BP-87 | BP-88 | BP-89 | BP-90 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 2.16 | 2.34 | 2.09 | 2.10 | 2.19 | 2.28 | 2.36 | 2.55 | 2.55 | 2.55 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 21.7 | 16.7 | 18.5 | 12.9 | 18.2 | 14.1 | 24.5 | 15.6 | 11.4 | 16.2 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.62 | 3.63 | 3.65 | 2.94 | 2.55 | 2.57 | 2.59 | 2.59 | 2.59 | 2.96 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 28.3 | 32.7 | 24.0 | 20.0 | 35.3 | 39.2 | 33.4 | 33.1 | 24.4 | 32.3 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.6 | 0.7 | 0.7 | 0.7 | 0.6 | 0.65 | 0.5 | 0.6 | 0.6 | 0.6 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 98.7 | 98.1 | 92.9 | 88.5 | 96.0 | 95.0 | 112.2 | 104.6 | 100.8 | 100.7 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 16.6 | 18.1 | 13.1 | 10.7 | 15.2 | 14.7 | - | 19.3 | 14.7 | 18.2 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 33.2 | 34.0 | 31.3 | 26.7 | 26.4 | 25.8 | 22.7 | 27.3 | 25.5 | 29.9 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-91 | BP-92 | BP-93 | BP-94 | BP-95 | BP-96 | BP-97 | BP-98 | BP-99 | BP-100 | Unit |
|----------------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 2.36 | 2.55 | 2.55 | 2.55 | 2.56 | 2.52 | 2.50 | 2.19 | 2.37 | 2.54 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 11.4 | 8.2 | 16.8 | 13.1 | 13.7 | 9.3 | 36.6 | 32.2 | 28.2 | 17.8 | mbar |
| $u_{0,FR}$ | FR gas velocity | 2.92 | 2.95 | 2.93 | 2.94 | 3.33 | 3.26 | 3.27 | 3.68 | 3.69 | 3.67 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 22.1 | 21.3 | 49.1 | 41.9 | 31.3 | 24.1 | 51.6 | 41.6 | 46.7 | 44.1 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.85 | 0.9 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 96.8 | 93.2 | 96.2 | 92.7 | 93.4 | 88.5 | 109.4 | 94.9 | 93.7 | 88.3 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 12.1 | 12.4 | 31.4 | 18.2 | 17.6 | 14.0 | - | 23.0 | 25.5 | 20.1 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 29.6 | 29.2 | 34.6 | 32.4 | 32.5 | 31.0 | 34.4 | 35.6 | 40.5 | 37.5 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-101 | BP-102 | BP-103 | BP-104 | BP-105 | BP-106 | BP-107 | BP-108 | BP-109 | BP-110 | Unit |
|----------------------|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 2.03 | 2.52 | 2.54 | 2.55 | 2.55 | 2.55 | 2.38 | 2.35 | 2.54 | 2.54 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 24.4 | 19.4 | 14.0 | 11.0 | 9.9 | 13.0 | 12.2 | 14.6 | 12.5 | 20.1 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.71 | 3.63 | 3.29 | 3.11 | 2.92 | 4.05 | 4.06 | 3.98 | 4.02 | 4.03 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 20.0 | 59.2 | 61.0 | 60.7 | 70.2 | 36.5 | 24.0 | 29.5 | 33.5 | 43.3 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 0.7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.95 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 84.2 | 81.9 | 77.2 | 72.4 | 71.4 | 76.6 | 67.1 | 73.1 | 75.3 | 84.2 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 12.1 | 25.9 | 20.2 | 15.9 | 14.0 | 17.1 | 13.9 | 16.6 | 16.7 | 22.2 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 27.7 | 41.7 | 38.2 | 39.5 | 33.2 | 40.6 | 32.4 | 36.6 | 37.3 | 39.9 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-111 | BP-112 | BP-113 | BP-114 | BP-115 | BP-116 | BP-117 | BP-118 | BP-119 | BP-120 | Unit |
|----------------------|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 2.55 | 2.55 | 2.38 | 2.38 | 2.39 | 2.22 | 2.36 | 2.36 | 2.54 | 2.37 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 12.2 | 18.2 | 20.3 | 14.1 | 12.7 | 14.1 | 6.9 | 10.4 | 8.3 | 8.9 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.32 | 3.29 | 3.33 | 2.90 | 2.96 | 4.09 | 4.01 | 4.02 | 4.04 | 3.66 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 45.6 | 74.6 | 60.9 | 62.2 | 53.1 | 17.6 | 12.4 | 21.2 | 17.1 | 16.5 | mbar |
| $\dot{V}_{J-valve}$ | Vol. flow of J-valve fluidization | 1 | 1 | 1 | 0.9 | 1 | 0.8 | 0.8 | 0.8 | 1 | 0.6 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 72.7 | 80.8 | 79.2 | 80.2 | 69.0 | 71.5 | 73.7 | 79.0 | 57.6 | 86.9 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 16.7 | 23.0 | 20.2 | 15.7 | 14.3 | 11.0 | 10.0 | 13.1 | - | 11.4 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 35.7 | 38.3 | 36.3 | 32.5 | 30.9 | 28.8 | 24.4 | 29.2 | 27.5 | 26.4 | kg/m ² s |

Cont'd: **Table S4.** Operating conditions for steady-state operating periods under investigation in CFM with bronze powder. CFM-BPX (steady-state operating period).

| Variable | Description | BP-121 | BP-122 | BP-123 | BP-124 | BP-125 | BP-126 | BP-127 | BP-128 | Unit |
|----------------------|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|---------------------|
| $u_{0,AR}$ | AR gas velocity | 2.54 | 2.55 | 2.19 | 2.20 | 2.20 | 2.67 | 2.67 | 2.69 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 12.1 | 8.4 | 6.8 | 6.1 | 4.9 | 15.4 | 27.9 | 17.1 | mbar |
| $u_{0,FR}$ | FR gas velocity | 3.29 | 2.94 | 3.98 | 3.66 | 3.31 | 3.93 | 3.98 | 4.00 | m/s |
| Δp_{FR} | FR pressure drop (inventory) | 37.8 | 31.5 | 7.5 | 7.6 | 7.5 | 53.6 | 68.6 | 60.7 | mbar |
| $V_{J-valve}$ | Vol. flow of J-valve fluidization | 0.9 | 0.9 | 0.5 | 0.5 | 0.5 | 1.2 | 1.2 | 1.3 | Nl/min |
| $\Delta p_{J-valve}$ | J-Valve pressure drop | 80.4 | 71.4 | 88.0 | 83.9 | 83.8 | 75.8 | 84.6 | 74.2 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 15.6 | 13.1 | 7.9 | 8.2 | 6.4 | 24.7 | 26.3 | 23.1 | kg/m ² s |
| $G_{s,FR}$ | FR Entrainment flux | 34.8 | 30.3 | 18.9 | 18.2 | 17.4 | 43.5 | 48.1 | 44.4 | kg/m ² s |

Table S5. Operating conditions for steady-state operating periods under investigation in CFM with ilmenite powder. CFM-BPX (steady-state operating period). BP130-133 (ILMf), BP134-137 (ILMc).

| Variable | Description | BP130 | BP131 | BP132 | BP133 | BP134 | BP135 | BP136 | BP137 | Unit |
|-----------------|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| $u_{0,AR}$ | AR gas velocity | 1.27 | 1.47 | 1.61 | 1.94 | 1.29 | 1.66 | 2.04 | 2.40 | m/s |
| Δp_{AR} | AR pressure drop (inventory) | 18.7 | 18.5 | 17.8 | 16.4 | 21.2 | 23.6 | 18.2 | 16.2 | mbar |
| $G_{s,AR}$ | AR Entrainment flux | 1.7 | 3.6 | 6.8 | 17.2 | 0.4 | 1.4 | 3.4 | 6.3 | m/s |