Supplementary material

Supplementary material 2: Optimization results; full data

Optimization of natural circulation district heating reactor primary heat exchangers

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1. Results, 200 MW Baseload

Heat exchanger dimensions and mass

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Tubesheet thickness:            54.0 mm

Shell diametre, inside         387.4 mm

Shell diametre, outside        406.4 mm

Shell thickness                  9.5 mm

Tube length, effective        2824.8 mm

Tube length, total            2969.5 mm

Tube diametre, outside          12.0 mm

Number of baffle plates           14

Baffle plate diametre          384.2 mm

Baffle plate thickness:          4.8 mm

Baffle spacing (centerlines)   192.8 mm

Baffle spacing (free space)    188.0 mm

Baffle spacing (S\_bf/D\_shell)  0.498

Tubes in window                   77

Tube rows in centre               14

Sealing strip pairs                2

Heat exchanger total mass        644 kg

Material costs per 1 heat exchanger

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shell [€]                     833

heat transfer tubes [€]     11220

baffle plate cost [€]         401

tube sheet cost [€]           970

other costs [€]               179

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total mat. costs [€]        13603

Processing costs per 1 heat exchanger

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beveling [€]                  173

cutting [€]                   382

drilling [€]                  535

bundle assembly [€]           810

other costs [€]              2049

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total processing costs [€]   3948

FOB cost

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manufacturing [€]           17552

overhead [€]                10531

contingency [€]              1755

transportation [€]           1755

profit [€]                   3510

VAT [€]                     11085

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Free-On-Board cost [€]      46188

* 1. Performance and cost data

The reactor pressure vessel and containment vessel costs refer to the bare pressure vessel costs alone; the costs of the reactor core assembly, control rods, and related equipment are not included, but are considered as part of the SMR base cost instead, as described in chapter 2.3.2 in the main article.

Results: performance data per single heat exchanger

(i.e. flow rate 1/16th of whole reactor)

Load point                           1       2       3       4       5       6

Primary water inlet T [°C]        150.00  143.96  139.71  137.18  139.71  143.11

Primary water outlet T [°C]       101.71   94.92   90.10   87.22   90.10   93.95

Secondary water inlet T [°C]       58.00   51.00   46.00   43.00   46.00   50.00

Secondary water outlet T [°C]     123.00  116.00  111.00  107.99  111.00  115.00

Primary mass flow rate [kg/s]      15.20   15.01   14.86   14.77   14.86   14.98

Secondary mass flow rate [kg/s]    11.43   11.45   11.46   11.46   11.46   11.45

Tube-side velocity [m/s]            0.44    0.43    0.42    0.42    0.42    0.43

Shell-side velocity (max) [m/s]     0.77    0.77    0.77    0.77    0.77    0.77

Prim.pressure drop, tubes [mbar]    8.61    8.46    8.35    8.29    8.35    8.44

Prim.pressure drop, core [mbar]     5.16    5.07    4.99    4.95    4.99    5.05

Sec. pressure drop (shell) [bar]    0.25    0.25    0.25    0.25    0.25    0.25

Heat transfr coeff, tube [W/m2K]    4388    4274    4188    4134    4188    4256

Heat transfr coeff, shell [W/m2K]  10293   10010    9798    9668    9798    9968

Heat transf.coeff overall [W/m2K]   1789    1755    1730    1714    1730    1750

Results: cost data

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Investment

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Total capital investment, heat exchangers          2.439 M€

Total capital investment, reactor pressure vessel  6.457 M€

Total capital investment, containment vessel      14.743 M€

Total capital investment, reactor pool cavity      3.068 M€

Total capital investment, SMR base cost           246.20 M€

Specific cost, whole system                       1719.1 €/kW\_th

Annual costs

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Investment amortization                          -37.878 M€

Fuel costs                                        -4.920 M€

Secondary water pumping cost                      -0.464 M€

Other operating and maintenance, variable         -1.640 M€

Other operating and maintenance, fixed            -6.000 M€

District heat sales profit                        114.80 M€

District heat price                                70.00 €/MWh

1. Results, 50 MW Baseload

Heat exchanger dimensions and mass

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Tubesheet thickness:            54.0 mm

Shell diametre, inside         387.4 mm

Shell diametre, outside        406.4 mm

Shell thickness                  9.5 mm

Tube length, effective        2819.5 mm

Tube length, total            2969.0 mm

Tube diametre, outside          12.0 mm

Number of baffle plates           15

Baffle plate diametre          384.2 mm

Baffle plate thickness:          4.8 mm

Baffle spacing (centerlines)   180.7 mm

Baffle spacing (free space)    175.9 mm

Baffle spacing (S\_bf/D\_shell)  0.466

Tubes in window                   77

Tube rows in centre               14

Sealing strip pairs                2

Heat exchanger total mass        646 kg

Material costs per 1 heat exchanger

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shell [€]                     833

heat transfer tubes [€]     11220

baffle plate cost [€]         430

tube sheet cost [€]           970

other costs [€]               179

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total mat. costs [€]        13632

Processing costs per 1 heat exchanger

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beveling [€]                  184

cutting [€]                   403

drilling [€]                  561

bundle assembly [€]           866

other costs [€]              2052

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total processing costs [€]   4066

FOB cost

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manufacturing [€]           17698

overhead [€]                10619

contingency [€]              1770

transportation [€]           1770

profit [€]                   3540

VAT [€]                     11177

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Free-On-Board cost [€]      46573

* 1. Performance and cost data

The reactor pressure vessel and containment vessel costs refer to the bare pressure vessel costs alone; the costs of the reactor core assembly, control rods, and related equipment are not included, but are considered as part of the SMR base cost instead, as described in chapter 2.3.2 in the main article.

Results: performance data per single heat exchanger

(i.e. flow rate 1/16th of whole reactor)

Load point                           1       2       3       4       5       6

Primary water inlet T [°C]        150.00  143.96  139.71  137.18  139.71  143.11

Primary water outlet T [°C]       101.71   94.92   90.10   87.22   90.10   93.95

Secondary water inlet T [°C]       58.00   51.00   46.00   43.00   46.00   50.00

Secondary water outlet T [°C]     123.00  116.00  111.00  107.99  111.00  115.00

Primary mass flow rate [kg/s]      15.20   15.01   14.86   14.77   14.86   14.98

Secondary mass flow rate [kg/s]    11.43   11.45   11.46   11.46   11.46   11.45

Tube-side velocity [m/s]            0.44    0.43    0.42    0.42    0.42    0.43

Shell-side velocity (max) [m/s]     0.77    0.77    0.77    0.77    0.77    0.77

Prim.pressure drop, tubes [mbar]    8.61    8.46    8.35    8.29    8.35    8.44

Prim.pressure drop, core [mbar]     5.16    5.07    4.99    4.95    4.99    5.05

Sec. pressure drop (shell) [bar]    0.25    0.25    0.25    0.25    0.25    0.25

Heat transfr coeff, tube [W/m2K]    4388    4274    4188    4134    4188    4256

Heat transfr coeff, shell [W/m2K]  10293   10010    9798    9668    9798    9968

Heat transf.coeff overall [W/m2K]   1789    1755    1730    1714    1730    1750

Results: cost data

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Investment

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Total capital investment, heat exchangers          2.439 M€

Total capital investment, reactor pressure vessel  6.508 M€

Total capital investment, containment vessel      14.836 M€

Total capital investment, reactor pool cavity      0.984 M€

Total capital investment, SMR base cost           93.300 M€

Specific cost, whole system                       2361.3 €/kW\_th

Annual costs

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Investment amortization                          -13.007 M€

Fuel costs                                        -1.230 M€

Secondary water pumping cost                      -0.116 M€

Other operating and maintenance, variable         -0.410 M€

Other operating and maintenance, fixed            -1.500 M€

District heat sales profit                        28.700 M€

District heat price                                70.00 €/MWh

1. Results, 50 MW Mid-load

Heat exchanger dimensions and mass

------------------------------------

Tubesheet thickness:            54.0 mm

Shell diametre, inside         387.4 mm

Shell diametre, outside        406.4 mm

Shell thickness                  9.5 mm

Tube length, effective        2824.0 mm

Tube length, total            2968.7 mm

Tube diametre, outside          12.0 mm

Number of baffle plates           14

Baffle plate diametre          384.2 mm

Baffle plate thickness:          4.8 mm

Baffle spacing (centerlines)   192.7 mm

Baffle spacing (free space)    187.9 mm

Baffle spacing (S\_bf/D\_shell)  0.498

Tubes in window                  105

Tube rows in centre               14

Sealing strip pairs                1

Heat exchanger total mass        643 kg

Material costs per 1 heat exchanger

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shell [€]                     833

heat transfer tubes [€]     11220

baffle plate cost [€]         388

tube sheet cost [€]           970

other costs [€]               158

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total mat. costs [€]        13568

Processing costs per 1 heat exchanger

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beveling [€]                  164

cutting [€]                   339

drilling [€]                  518

bundle assembly [€]           729

other costs [€]              1981

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total processing costs [€]   3730

FOB cost

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manufacturing [€]           17299

overhead [€]                10379

contingency [€]              1730

transportation [€]           1730

profit [€]                   3460

VAT [€]                     10926

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Free-On-Board cost [€]      45523

* 1. Performance and cost data

The reactor pressure vessel and containment vessel costs refer to the bare pressure vessel costs alone; the costs of the reactor core assembly, control rods, and related equipment are not included, but are considered as part of the SMR base cost instead, as described in chapter 2.3.2 in the main article.

Results: performance data per single heat exchanger

(i.e. flow rate 1/16th of whole reactor)

Load point                           1       2       3       4       5       6

Primary water inlet T [°C]        150.00  143.96  139.70  121.88  108.95  107.30

Primary water outlet T [°C]       101.99   95.20   90.39   80.53   81.85   83.79

Secondary water inlet T [°C]       58.00   51.00   46.00   43.00   46.00   50.00

Secondary water outlet T [°C]     123.00  116.00  111.00  100.00  100.00  100.00

Primary mass flow rate [kg/s]      15.28   15.09   14.95   12.79    9.79    9.02

Secondary mass flow rate [kg/s]    11.43   11.45   11.46    9.35    4.93    4.26

Tube-side velocity [m/s]            0.44    0.43    0.42    0.36    0.27    0.25

Shell-side velocity (max) [m/s]     0.77    0.77    0.77    0.62    0.33    0.29

Prim.pressure drop, tubes [mbar]    8.69    8.55    8.44    6.50    4.07    3.53

Prim.pressure drop, core [mbar]     5.14    5.04    4.97    3.84    2.43    2.11

Sec. pressure drop (shell) [bar]    0.23    0.23    0.23    0.16    0.05    0.04

Heat transfr coeff, tube [W/m2K]    4411    4295    4209    3544    2432    2082

Heat transfr coeff, shell [W/m2K]   9971    9697    9493    7942    5232    4800

Heat transf.coeff overall [W/m2K]   1783    1750    1725    1528    1143    1026

Results: cost data

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Investment

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Total capital investment, heat exchangers          2.404 M€

Total capital investment, reactor pressure vessel  6.530 M€

Total capital investment, containment vessel      14.876 M€

Total capital investment, reactor pool cavity      0.989 M€

Total capital investment, SMR base cost           93.300 M€

Specific cost, whole system                       2362.0 €/kW\_th

Annual costs

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Investment amortization                          -13.011 M€

Fuel costs                                        -0.891 M€

Secondary water pumping cost                      -0.088 M€

Other operating and maintenance, variable         -0.297 M€

Other operating and maintenance, fixed            -1.500 M€

District heat sales profit                        20.790 M€

District heat price                                70.00 €/MWh