the Conference IEEC 2026

Advanced mathematical model for heat exchange in CFB boiler ash cooler

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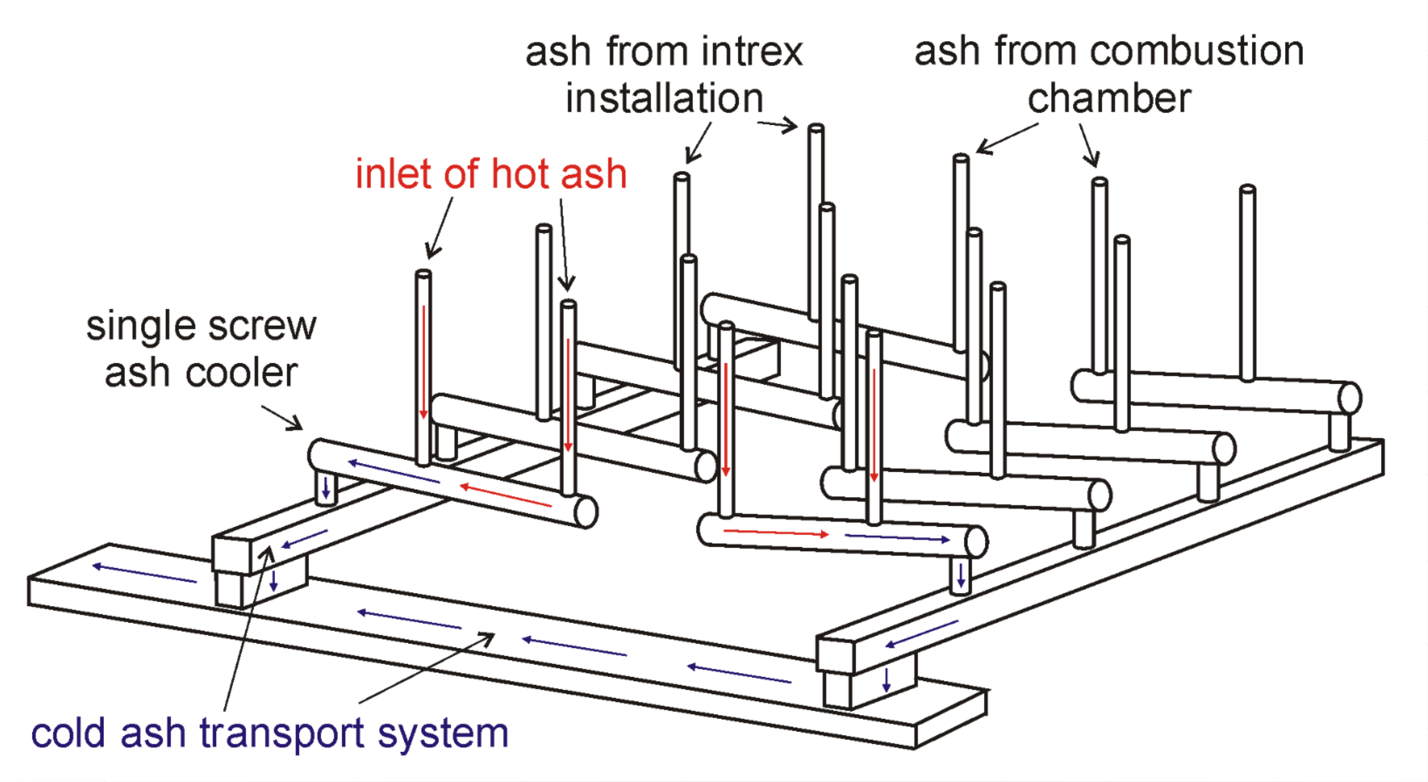
Outline of the presentation

- Introduction to the issue
- 1D mathematical model of single screw ash cooler (SSAC)
  - Heat and mass transfer equation
  - Schlünder model
  - Validation of the mathematical model
- Standard calculations
- Advanced calculations
- Summary

Introduction to the issue

Single screw ash cooler working with a circulating fluidized bed boiler

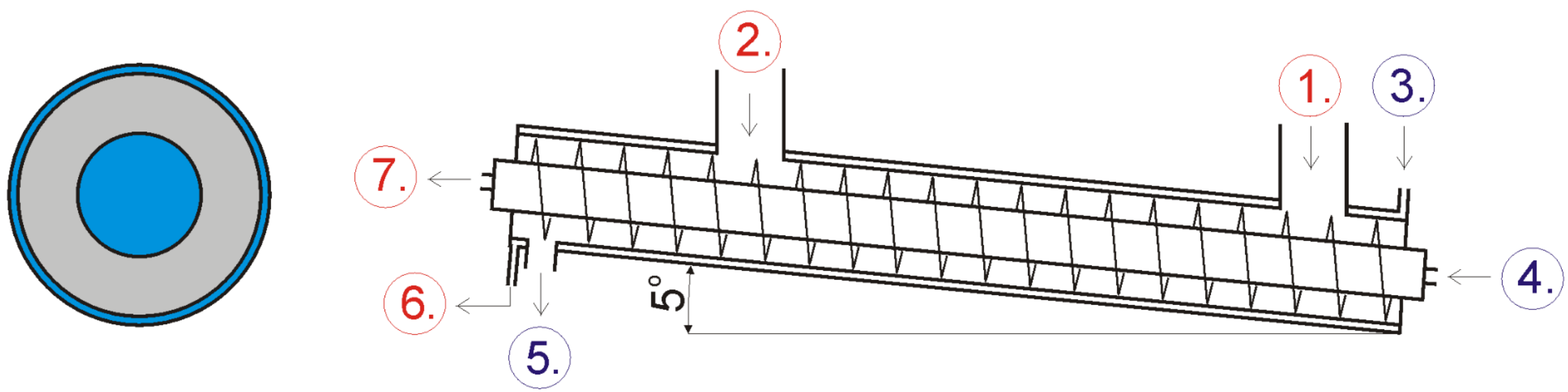


temperature of hot ash $t_{a,i} \approx 600\ °C$

temperature of cold ash $t_{a,o} \approx 120\ °C$

Introduction to the issue

Construction of the single screw ash cooler – co-flow heat exchanger



1. inlet of hot ash, 2. inlet of hot ash from intrex; 3., 4. inlets of cold water (coolant); 5. outlet of cold ash; 6., 7. outlets of hot water

1D mathematical model

Thermal balance between hot ash and cold water

$$\rho_{b,a} \cdot C_a \cdot q_{va} \cdot (t_{a,i} - t_{a,o}) = \rho_w \cdot C_w \cdot (q_{vw,s} \cdot (t_{w,so} - t_{w,si}) + q_{vw,c} \cdot (t_{w,co} - t_{w,ci}))$$

ρ - density (*w*, *a* - water and ash, respectively)

C – specific heat of the materials

t – temperature (*i*, *o* – at the inlet and outlet, respectively)

q_v – volumetric flow rate (*w*, *a* - water and ash, respectively)

s, *c* – shaft (screw), casing

1D mathematical model

Dimensionless coefficient of filling the SSAC cross-section with ash - $\varepsilon(n)$

$$q_{va} = \varepsilon \cdot S \cdot u$$

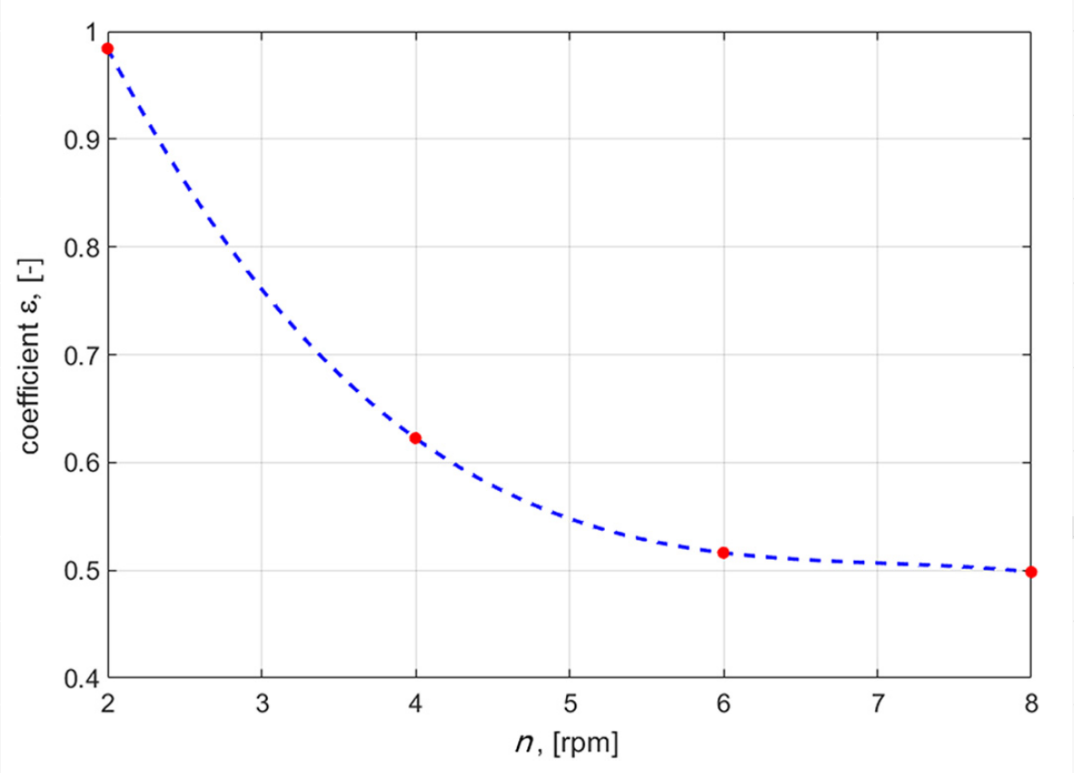
S – total area of screw

u – ash transport velocity

$$u = n \cdot d$$

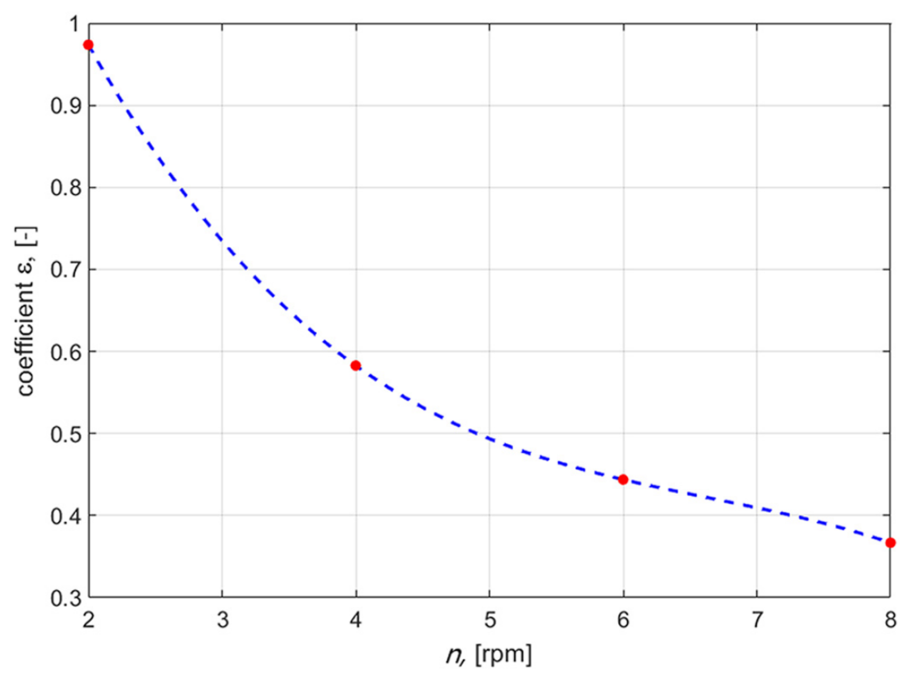
n – rotation velocity of the screw

d – screw pitch

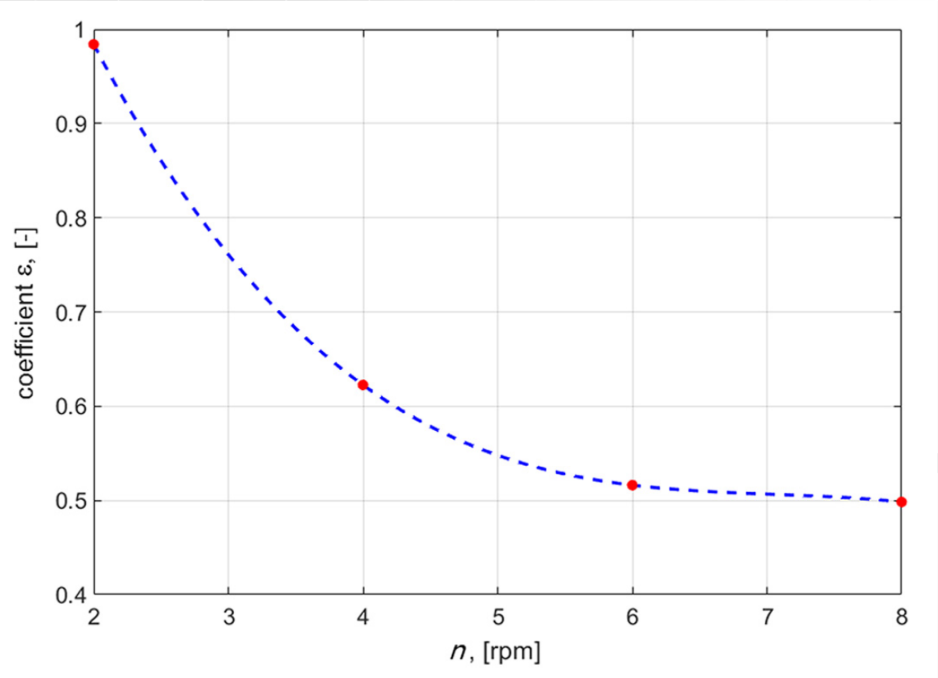


1D mathematical model

Dimensionless coefficient of filling - $\varepsilon(n)$

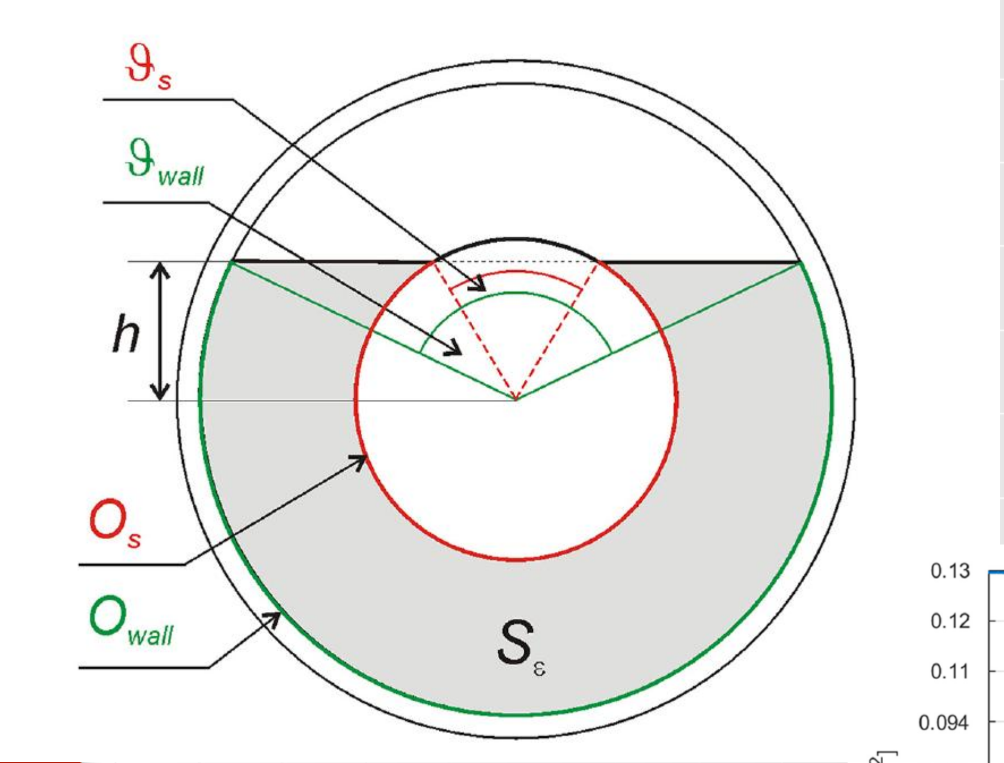


sideway ash cooler

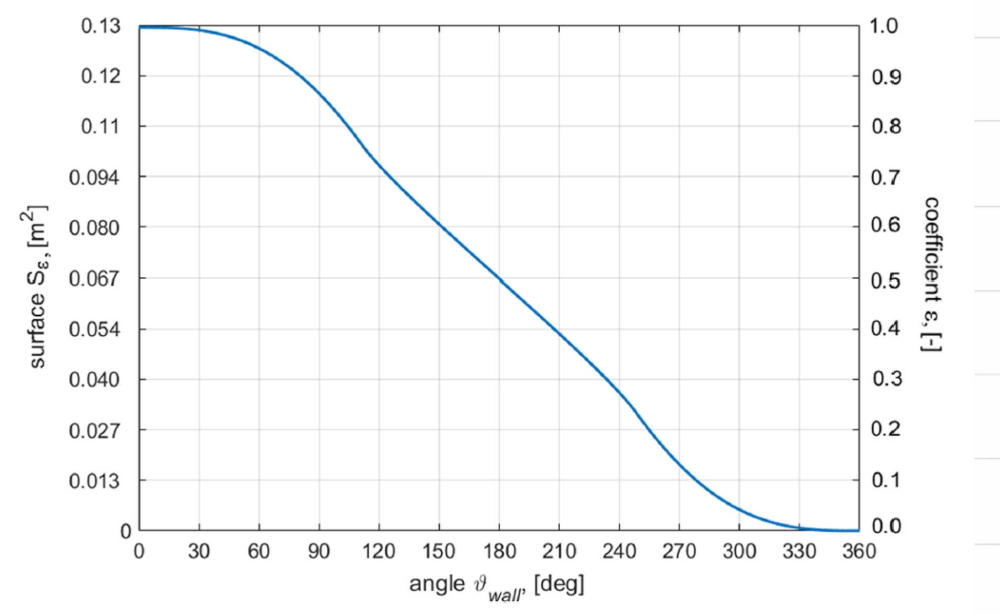


middle ash cooler

1D standard mathematical model



Cross-section of the single screw ash cooler



Schlünder model

Heat transfer coefficient for ash α_a

$$\alpha_a = 2\sqrt{\frac{\lambda_a \cdot \rho_{b,a} \cdot C_a}{\pi \cdot T}}$$

λ_a – thermal conductivity of ash

$$T = \frac{N_{mix}}{n}$$

where

$$N_{mix} = c \cdot \left(\frac{(2\pi \cdot n)^2 \cdot D}{2g} \right)^x$$

T – time constant, *n* – rotation velocity,

c, x – empirical parameters in the ash mixing model

Schlünder model

- λ_a = 0.7 W/(kg·deg)
- C_a = 1005 J/(kg·deg)
- $\rho_{b,a}$ = 1021 kg/m^3

c = 4

Rotation velocity n, [rpm]	2	4	6	8
Parameter x for SSAC no. 1, [−]	0.175	0.315	0.459	0.460
Parameter x for SSAC no. 2, [−]	0.098	0.260	0.425	0.520
α_a for SSAC no. 1, W/(m^2·K)	160.9	298.4	454.2	460.5
α_a for SSAC no. 2, W/(m^2·K)	122.7	255.8	418.6	522.7

Numerical vs. experimental results

Rotation velocity n, rpm	2	4	6	8
Mixing parameter x, [−]	0.175	0.315	0.459	0.460
Outlet temperature of the ash – model t_a, °C	87.4	97.8	103.6	131.0
Outlet temperature of the ash – experiment t_a, °C	88.4	98.4	107.0	134.4
Relative error e, %	1.12	0.57	3.22	2.47
Outlet temperature of the cooling water inside the screw – model $t_{w,s}$, °C	49.8	58.5	64.8	69.0
Outlet temperature of the cooling water inside the screw – experiment $t_{w,s}$, °C	52.1	60.1	67.1	70.3
Relative error e, %	4.42	2.70	3.52	1.87
Outlet temperature of the cooling water inside the casing – model $t_{w,c}$, °C	47.8	52.4	60.0	64.3
Outlet temperature of the cooling water inside the casing – experiment $t_{w,c}$, °C	46.1	51.1	57.5	62.1
Relative error e, %	3.59	2.65	4.40	3.56
Total heat flux transfer to the cooling water Q_w - model, kW	255.4	323.9	402.4	451.5
Total heat flux transfer to the cooling water Q_w - experiment, kW	245.3	310.7	380.3	425.3
Relative error e, %	4.11	4.25	5.80	6.17

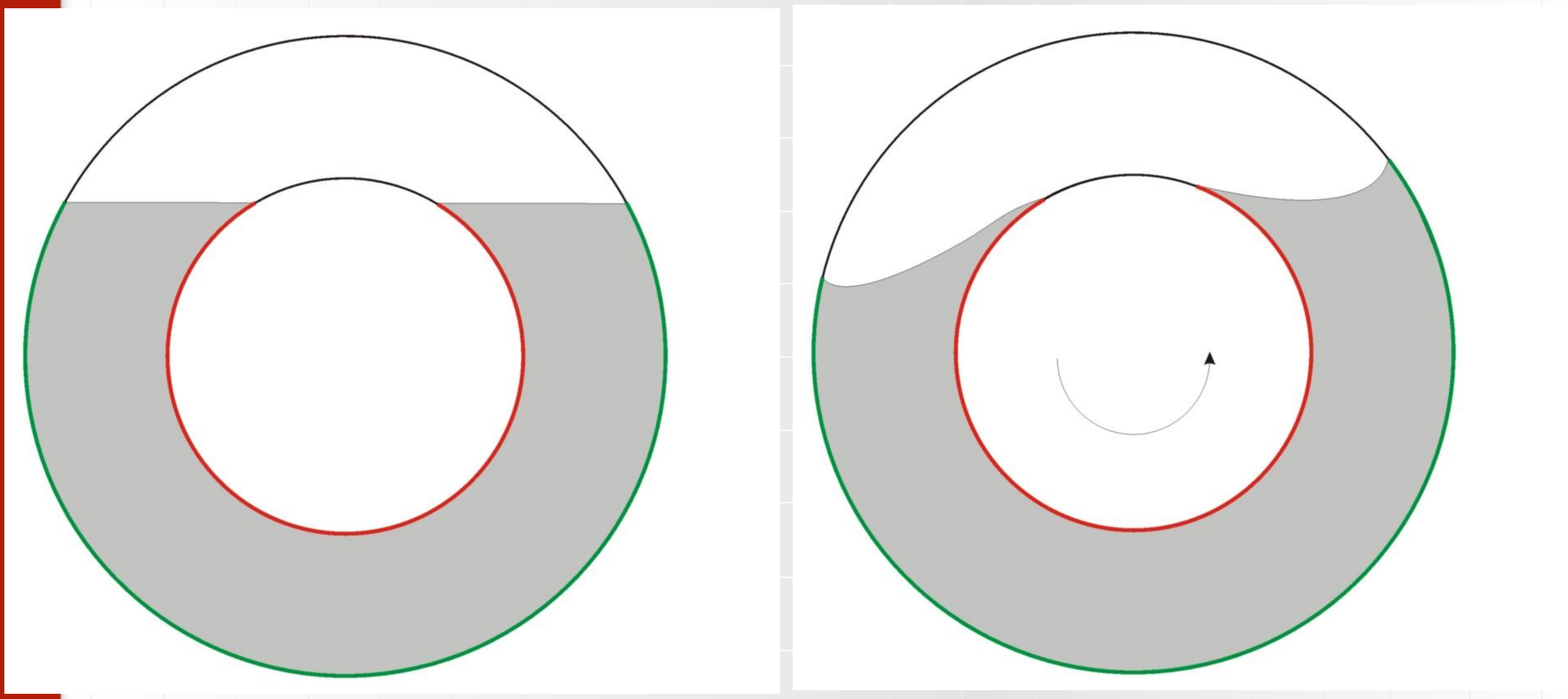
SSAC no. 1

Numerical vs. experimental results

Rotation velocity n, rpm	2	4	6	8
Mixing parameter x, [−]	0.098	0.260	0.425	0.520
Outlet temperature of the ash – model t_a, °C	109.6	107.0	114.0	125.1
Outlet temperature of the ash – experiment t_a, °C	109.7	107.9	115.7	124.3
Relative error e, %	0.01	0.78	1.47	0.67
Outlet temperature of the cooling water inside the screw – model $t_{w,s}$, °C	46.7	50.5	53.4	56.4
Outlet temperature of the cooling water inside the screw – experiment $t_{w,s}$, °C	47.3	51.7	55.2	59.0
Relative error e, %	1.31	2.40	3.33	4.36
Outlet temperature of the cooling water inside the casing – model $t_{w,c}$, °C	53.6	60.4	67.0	72.1
Outlet temperature of the cooling water inside the casing – experiment $t_{w,c}$, °C	52.4	58.6	64.2	69.2
Relative error e, %	2.34	3.11	4.34	4.13
Total heat flux transfer to the cooling water Q_w - model, kW	208.8	262.0	307.8	343.8
Total heat flux transfer to the cooling water Q_w - experiment, kW	207.2	261.0	305.4	345.0
relative error e, %	0.74	0.39	0.77	0.35

SSAC no. 2

Standard vs. advanced model



Standard vs. advanced model

Rotation velocity n, rpm	2	4	6	8
Outlet temperature of ash – experiment t_a, °C	**88.4**	**98.4**	**107.0**	**134.4**
Outlet temperature of ash – dynamic model t_a, °C	**88.6**	**98.7**	**107.9**	**135.5**
Outlet temperature of ash – static model t_a, °C	87.4	97.8	103.4	131.0
Outlet temperature of cooling water inside the screw – experiment $t_{w,s}$, °C	**52.1**	**60.1**	**67.1**	**70.3**
Outlet temperature of cooling water inside the screw – dynamic model $t_{w,s}$, °C	**51.2**	**59.8**	**66.4**	**70.8**
Outlet temperature of cooling water inside the screw – static model $t_{w,s}$, °C	49.8	58.5	64.8	69.0
Outlet temperature of cooling water inside the casing – experiment $t_{w,c}$, °C	**46.1**	**51.1**	**57.5**	**62.1**
Outlet temperature of cooling water inside the casing – dynamic model $t_{w,c}$, °C	**46.8**	**51.5**	**58.2**	**62.2**
Outlet temperature of cooling water inside the casing – static model $t_{w,c}$, °C	47.8	52.4	60.0	64.3

SSAC no. 1

Standard vs. advanced model

Rotation velocity n, rpm	2	4	6	8
Outlet temperature of ash – experiment t_a, °C	**109.7**	**107.9**	**115.7**	**124.3**
Outlet temperature of ash – dynamic model t_a, °C	**110.7**	**107.8**	**115.7**	**126.3**
Outlet temperature of ash – static model t_a, °C	109.6	107.0	114.0	125.1
Outlet temperature of cooling water inside the screw – experiment $t_{w,s}$, °C	**47.3**	**51.7**	**55.2**	**59.0**
Outlet temperature of cooling water inside the screw – dynamic model $t_{w,s}$, °C	**46.8**	**51.6**	**55.3**	**58.9**
Outlet temperature of cooling water inside the screw – static model $t_{w,s}$, °C	46.7	50.5	53.4	56.4
Outlet temperature of cooling water inside the casing – experiment $t_{w,c}$, °C	**52.4**	**58.6**	**64.2**	**69.2**
Outlet temperature of cooling water inside the casing – dynamic model $t_{w,c}$, °C	**53.3**	**59.2**	**64.8**	**69.4**
Outlet temperature of cooling water inside the casing – static model $t_{w,c}$, °C	53.6	60.4	67.0	72.1

SSAC no. 2

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Summary

- The operating conditions of CFB boiler force the work of the SSAC heat exchanger with different fillings with ash. The ash filling characteristics $\varepsilon(n)$ is the individual curve for each SSAC obtained from experimental data.
- The key element of the mathematical model is Schlünder model which defines a heat transfer coefficient for ash taking into account the local dynamic mixing process inside the ash cooler. The numerical results verify that the mixing model proposed by Schlünder correctly predicts the local value of the heat transfer coefficient for ash and confirm that this parameter plays a key role in the heat transfer processes inside the device.
- The movement of the ash inside the ash cooler takes place under the influence of a complex displacement involving both translational and rotational motion. The advanced approach to the heat exchange processes inside the ash cooler is more compatible with experimental data than the standard model.

P. Regucki, R. Krzyżyńska and Z. Szeliga, *Mathematical model for a single screw ash cooler of a circulating fluidized bed boiler*, *Powder Technology, 396 (2022)*, https://doi.org/10.1016/j.powtec.2021.10.044