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COOLING WATER FLOW RATE IMPACT ON WATER VAPOR CONDENSATION FROM FLUE GAS IN A VERTICAL TUBE WITH WATER INJECTION

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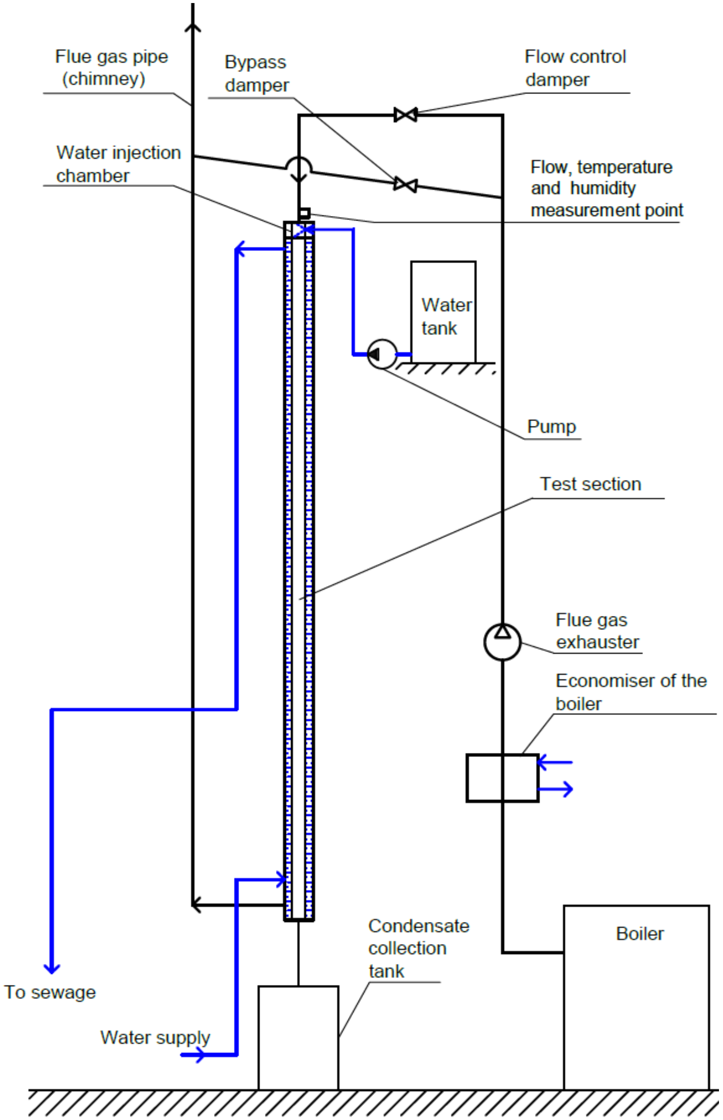
Introduction (1)

- During the last decades, the energy policy of most countries has been focused on:
  - the increase of energy efficiency;
  - the reduction of greenhouse gas emissions;
  - the use of renewable energy sources.

Introduction (2)

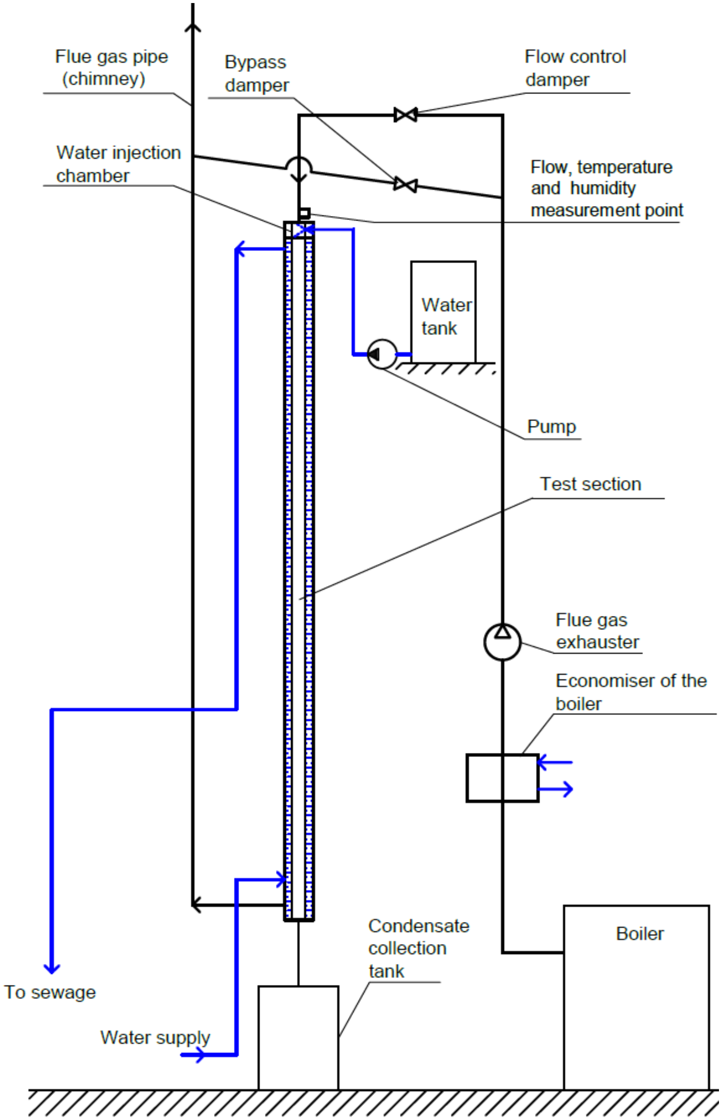
- Waste heat recovery from flue gas based on water vapor condensation is an important issue.
- Waste heat recovery significantly increases the efficiency of thermal power units and other industrial processes.
- Heat recovery efficiency is controlled by using condensing heat exchangers.

Experimental setup (1)



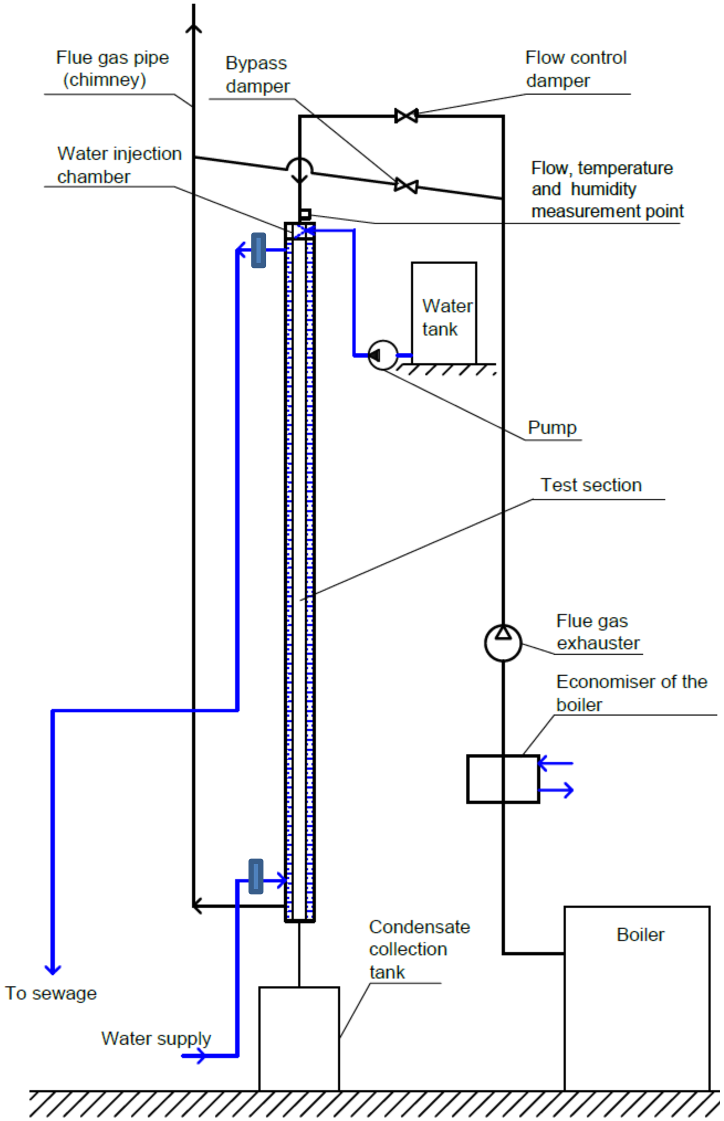
- Incineration of wood pellets in automatic boiler (50 kW).
- The test section composed of long stainless steel vertical tubes.
- Internal calorimetric tube (length x ≈ 5.8 m, inner diameter d = 0.034 m, x/d ≈ 170, wall thickness δ = 2 mm).
- Outer tube (length x ≈ 5.9 m, inner diameter D = 0.108 m).
- Water injection into the gas flow before the inlet into the calorimetric tube.
- Municipal cooling water supply into the space between the inner and outer tubes.
- Counter-current flow arrangement.
- Flue gas, water flow rates adjustment by dampers.

Experimental setup (2)



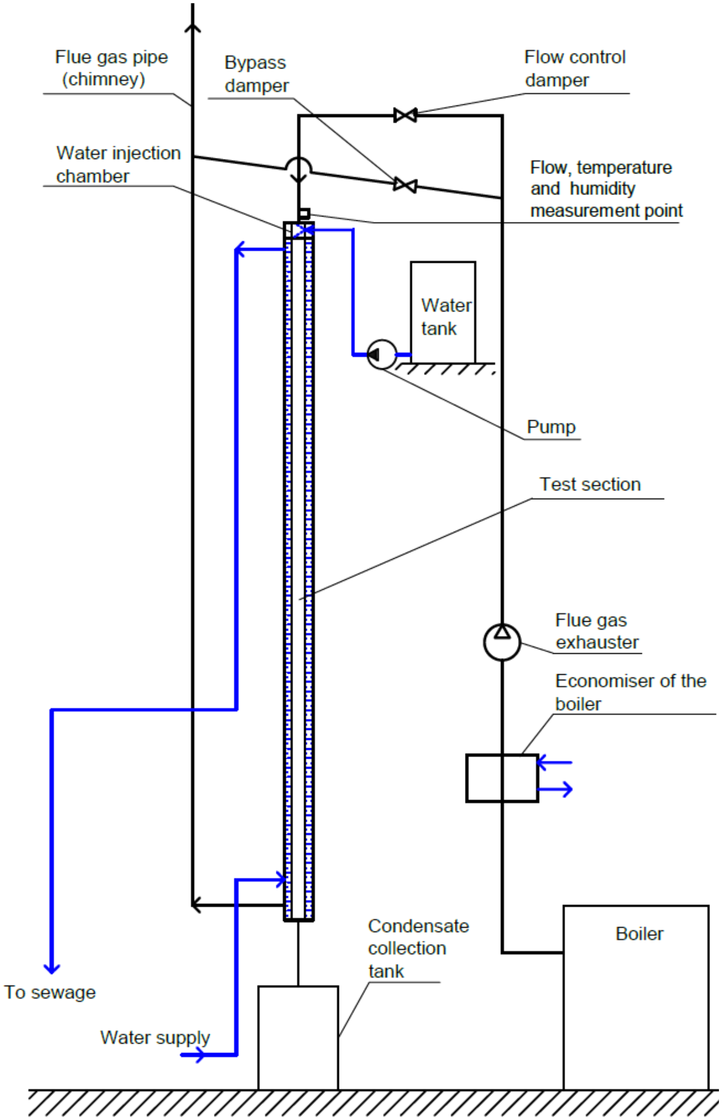
- Flue gas water vapor mass fraction was 15-16 %.
- Flue gas flow rate at the inlet into the experimental section – ≈50 m^3/h ($Re_{in}=20500$).
- Cooling water flow rate:
  - 1 l/min (60 kg/h);
  - 2 l/min (120 kg/h).
- Additional injection of water into flue gas before the calorimetric tube (one nozzle, flow rate ≈0.52 l/min, t ≈ 40 °C).

Methodology (1)



- 20 thermocouples installed in the centre of the calorimetric tube to measure the flue gas temperature along the tube.
- 20 thermocouples installed in the inner wall of the calorimetric tube along the length of the tube.
- 10 thermocouples installed between the inner and the outer tubes to measure cooling water temperature.
- 3 thermocouples installed in each of the water mixers to measure the inlet and outlet water temperatures.

Methodology (2)

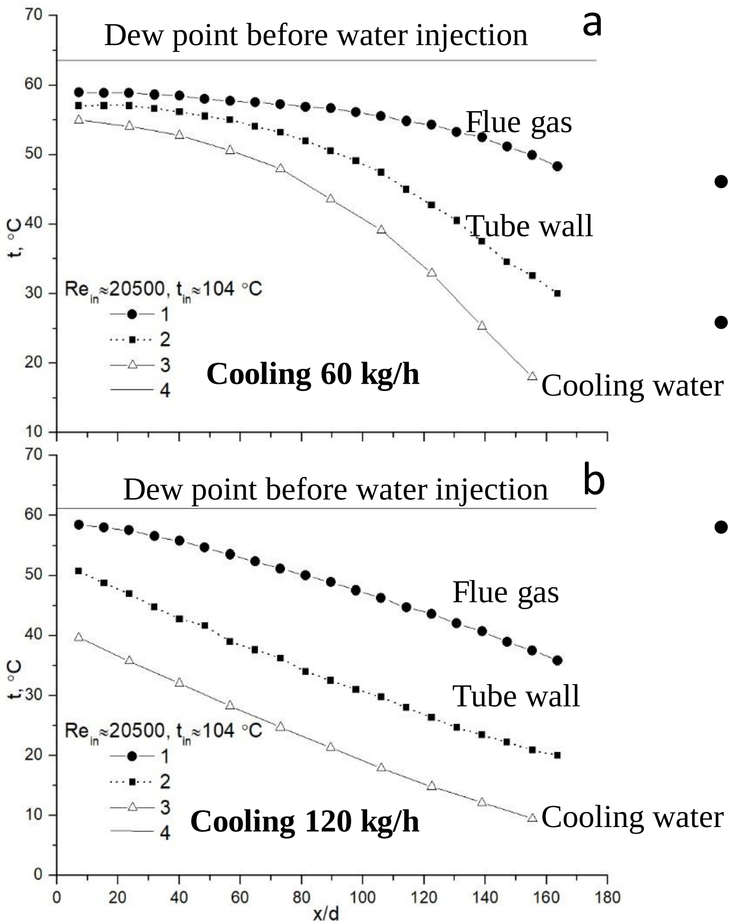


- KIMO C310 sensor used to measure flue gas temperature (t_{in}, °C) and relative humidity (RH_{in}, %) at the inlet into the experimental section.
- Flue gas flow rate at the inlet measured using a bellmouth with installed Pitot-Prandtl's tubes, connected to the micromanometer.
- The flow rate of the cooling water determined by the weighting method.
- The flow rate of the collected condensate determined by the weighting method.

Methodology (3)

- The total local heat flux was obtained as: $q_{t_i} = \frac{m_{H2O_i} \cdot c_{pH2O_i}}{\pi \cdot d} \cdot \left(\frac{dt_{H2O}}{dx}\right)_i$
- The local total heat transfer coefficient was calculated as: $\alpha_{t_i} = \frac{q_{t_i}}{(t_c - t_w)_i}$
- The total Nusselt number: $Nu_{t_i} = \alpha_{t_i} \cdot d/\lambda_i$
- Flue gas Reynolds number at the inlet to the calorimetric tube: $Re_{in} = u_{in} \cdot d/\nu_{in}$
- The condensate mass flow rate was obtained as: $m_{cd} = \frac{m_{\Sigma} - m_{\mathrm{inj}}}{\tau} \cdot 100$
- Condensation efficiency (%): $n_{cd} = \frac{m_{cd}}{m_{H2O_{in}}} \cdot 100$

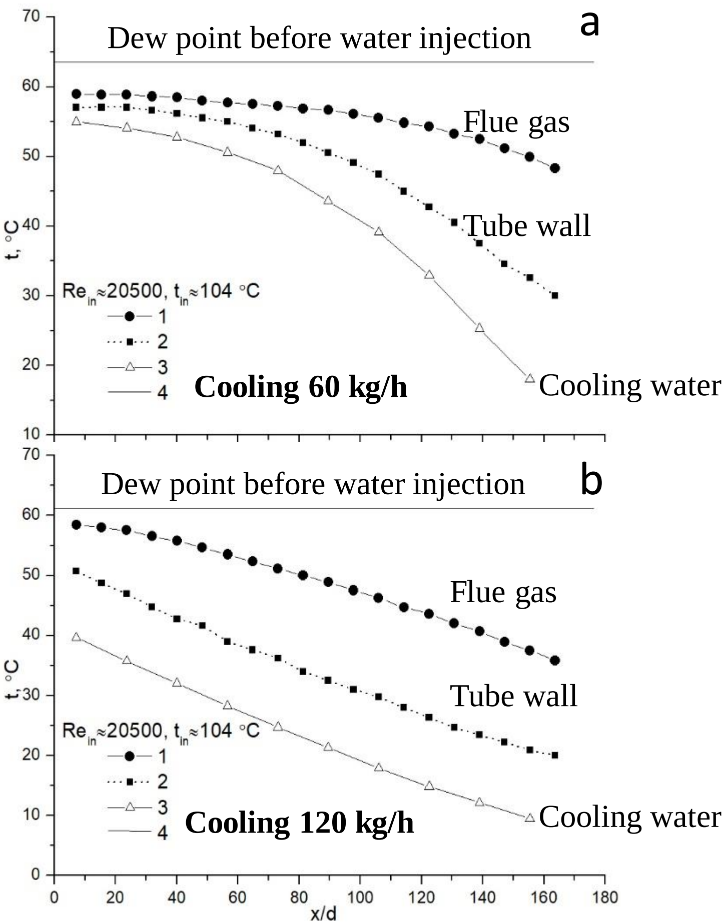
Results (1)



Temperature distribution along the tube at different cooling water flow rates

- For all the cases presented in Figure, the tube wall temperature is lower the dew point temperature.
- For different cooling water flow rates the characters of temperatures distributions along the test section differ significantly.
- In the calorimetric tube, the flue gas temperature decreases slightly from the inlet until x/d ≈ 110 (Figure a) and after that, a more pronounced decrease is observed.

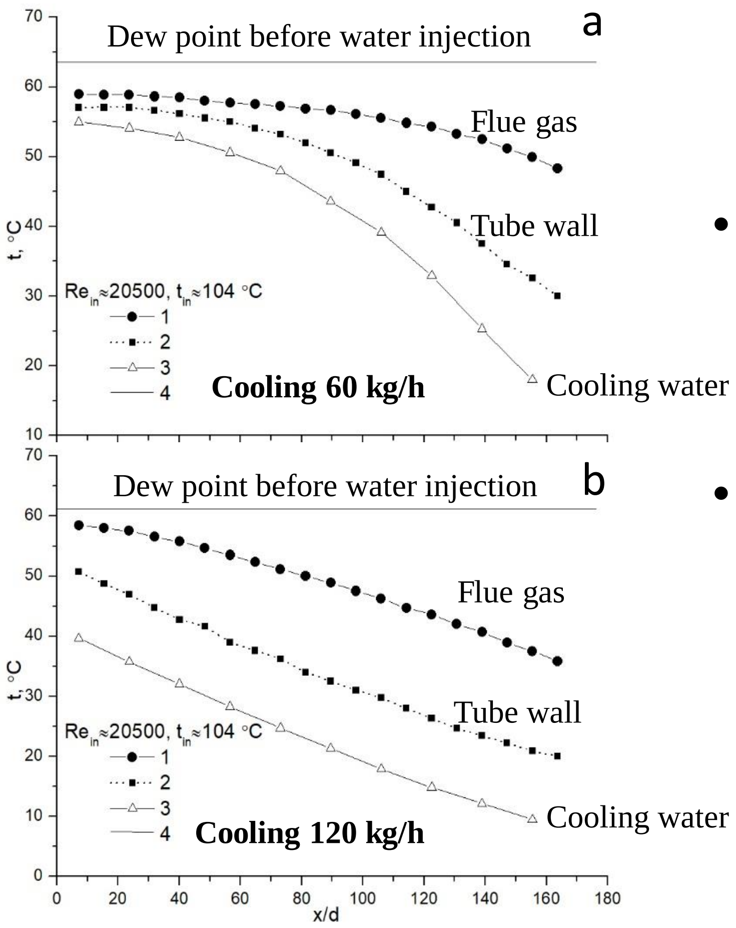
Results (2)



Temperature distribution along the tube at different cooling water flow rates

- The cooling water temperature indicates that the water is gaining heat rather intensively from the inlet (x/d ≈ 170) until x/d ≈ 50 (Figure a).
- In this region, the water temperature increases by about 35 °C (from 15 to 50 °C).
- From x/d ≈50 until the outlet, the water temperature increased insignificantly, i.e., by ≈ 5 °C, up to ≈ 55 °C.
- The tube wall temperature character (Figure a) is similar to the cooling water temperature character.

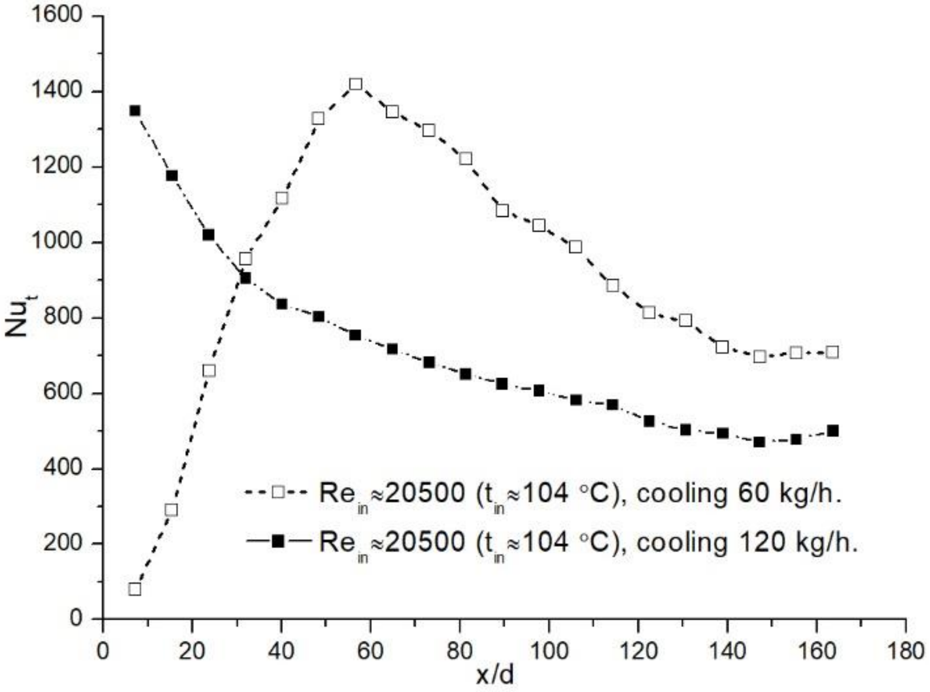
Results (3)



Temperature distribution along the tube at different cooling water flow rates

- The character of the tube wall and cooling water temperature variation along the tube (Figure b) are almost the same as the character of flue gas temperature.
- Temperature differences between flue gas and tube wall, and between tube wall and cooling water, are almost constant through all the length of the model of the condensing heat exchanger (Figure b).

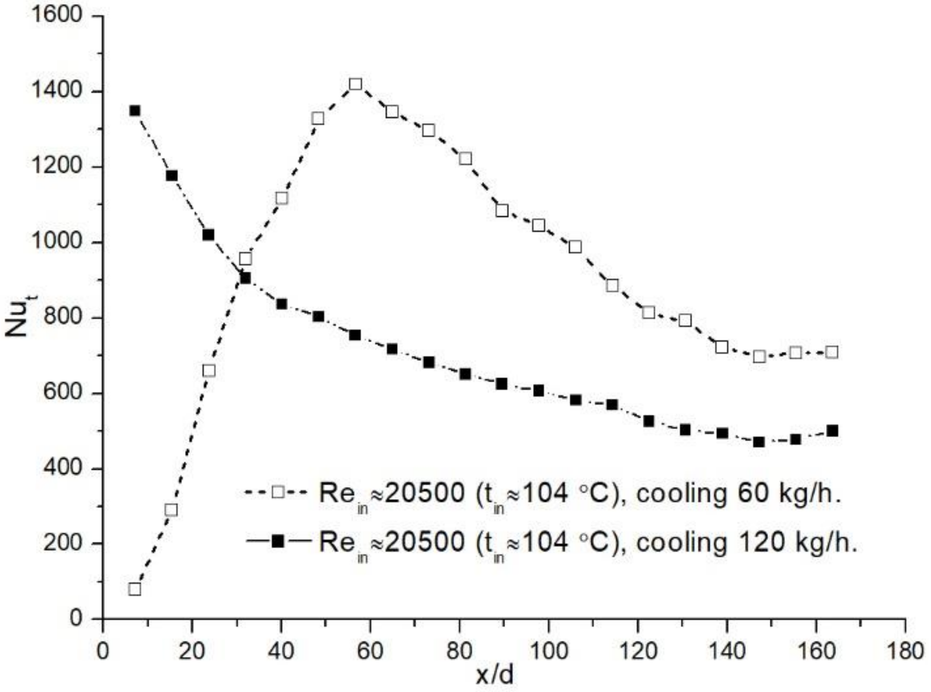
Results (4)



Distribution of the total local Nusselt number along the tube at different cooling water flow rates and the same inlet flue gas temperature

- For both cooling water flow rates condensation occurs at the beginning of the calorimetric tube.
- At the beginning of the tube Nu_t differs for about 15 times for different cooling water flow rates.
- For lower cooling water flow rate Nu_t increases rapidly until x/d ≈ 60 (Nu_t reaches ≈ 1450).
- From x/d=60 Nu_t decreases gradually until the end of the tube.
- The increase indicates intense condensation and then, as the water vapor is being condensed, the heat transfer gradually decreases.
- At the end of the tube, Nu_t is still high – about 800.

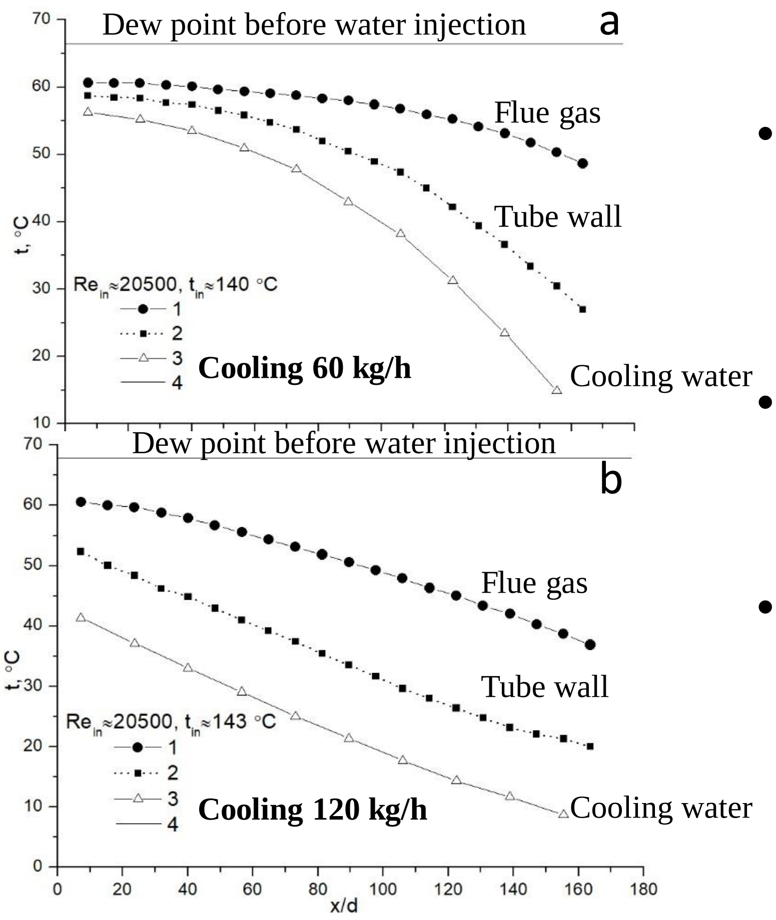
Results (5)



Distribution of the total local Nusselt number along the tube at different cooling water flow rates and the same inlet flue gas temperature

- For higher cooling water flow rate the most intense condensation heat transfer is achived at the beginning of the tube.
- Nu_t gradually decreases along the tube due to the decreased amout of water vapor which could be condensed.
- At the end of the tube Nu_t decreases to about 500.
- Condensation efficiencies were determined to be about 52 % and 65% for cooling water flow rates of 60 and 120 kg/h, respectively.

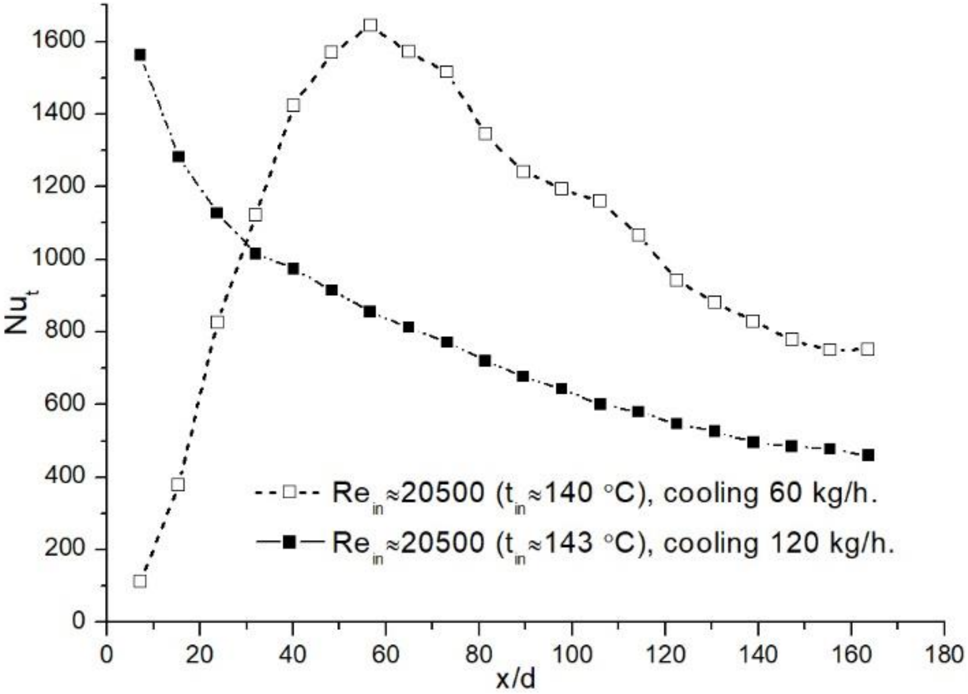
Results (6)



Temperature distribution along the tube at different cooling water flow rates

- In case of higher inlet flue gas temperature for all the cases presented in Figure, the tube wall temperature is lower the dew point temperature (line 4).
- Characters of tempeartures distributions in this case is very similar to those, discussed for lower inlet flue gas temperature.
- The difference is that all the temperatures are higher for few degrees.

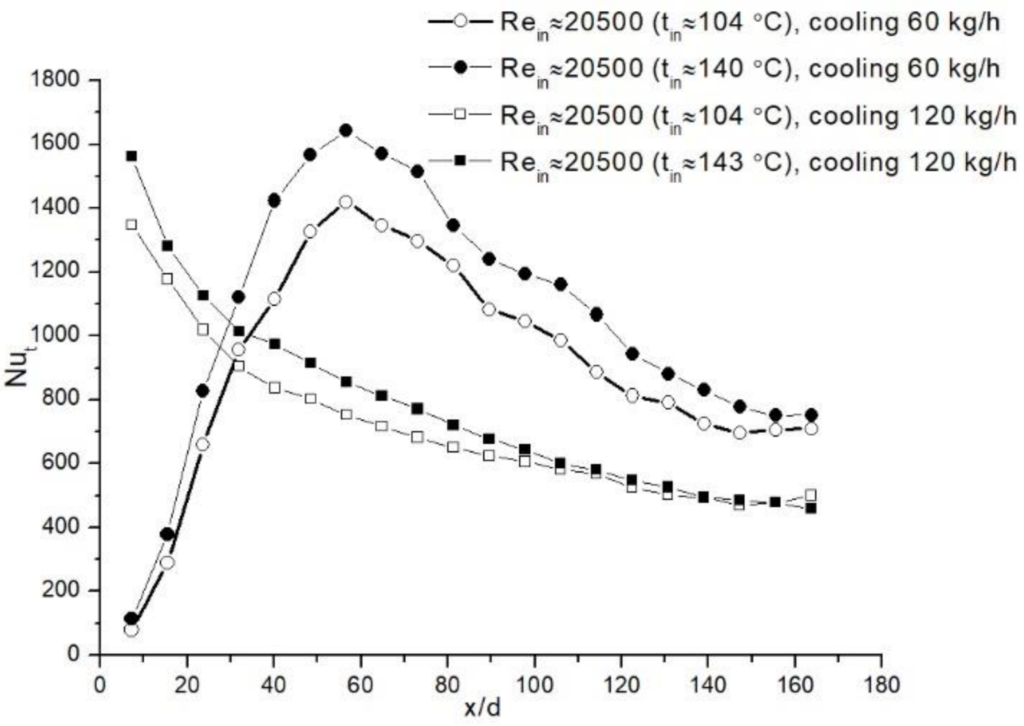
Results (7)



Distribution of the total local Nusselt number along the tube at different cooling water flow rates and the same inlet flue gas temperature

- The tendencies of Nu_t variation along the tube in this case are very similar to those obtained in case of lower inlet flue gas temperature.
- Condensation efficiencies were determined to be about 45 % and 55% for cooling water flow rates of 60 and 120 kg/h, respectively.

Results (8)



Comparison of distribution of the total local Nusselt number along the tube at different cooling water flow rates and different inlet flue gas temperature

- Higher inlet flue gas temperature results in higher Nu_t along the tube.
- Nu_t is more pronounced (especially in x/d range between ≈30-150) in case of lower cooling water flow rate.
- Nu_t at the end of the tube (from x/d>100) in case of higher cooling water flow rate does not depend on inlet flue gas temperature.
- Condensation efficiency at lower inlet temperature is about 10 % higher.

Conclusions

After analysis, the following conclusions can been made:

- Performed investigations revealed the pecularities of the local total Nusselt number during different cooling water flow rates in vertical tube with water injection.
- The change of cooling water flow rate drastically changes the distribution of total Nusslet number along the tube.
- At higher flue gas inlet temperatures, the effect of cooling water flow rate on Nu_t is also stronger. For lower cooling water flow rate the effect is more pronounced in the middle part of the tube ($x/d \approx 20$-150), and for higher cooling water flow rate, it is in the x/d range between 0 and 100.
- The higher cooling water flow rate results in condensation efficiencies for about 10% higher in comparison to those in case of lower cooling water flow rate.
- Condensation efficiency at lower inlet temperature is about 10 % higher.

Thank you for the attention

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