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Potential for Particulate Emission Reduction in Flue Gas Condensing Heat Exchangers in Biomass-Fired Boiler

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Introduction

Direct biomass combustion for the production of heat is a broad field of technology which ranges from residential wood stoves to commercial and industrial boilers and furnaces. Fuels typically include pellets, chips and cord wood. Over the past decade, as a result of fuel price advantages and other benefits, wood burning has seen a significant growth. Renewable energy sources have become the primary focus of global energy consumption which is why wood burning has become more advantageous. Regional job creation would also occur as an effect of the growth in this industry. Along with this trend there is concern about air pollutant emissions and impact on air quality (Weiss, Rector et al. 2016). The focus of this work is on particulate emissions from biomass combustion with wood pellet fuels. Of the biomass fuels, pellets have the lowest uncontrolled emissions (McDonald 2009, Chandrasekaran, Laing et al. 2011).

In gas- and oil-fired heating systems, very high efficiency is now commonly achieved using condensing heat exchangers. These achieve high efficiency by recovering both sensible and latent heat from the flue gas. Condensing in these systems occurs on the cooled heat exchanger surfaces which are below the local water vapor saturation temperature. The condensation rate, then, is a strong function of the boiler water temperature and the heat transfer conditions (convection coefficient, materials, geometry).

In addition to capturing heat, these systems also have the potential to capture pollutants including condensable and particles by the mechanisms of absorption, condensation, and impaction as they are cooled below the dew point (Johnson, Myers et al. 1995). These pollutants can then be removed with the condensed water for separation or disposal.

For condensable pollutants, as the gas is cooled, these may form droplets in the gas stream or they may diffuse to the wall before condensing. For the purpose of removal, it is more desirable for these to condense on the wall because the aerosols formed in the gas stream are very small and relatively difficult to remove.

Most of the mass of these pollutants at the exit of the boiler primary heat exchanger, i.e. entering the condensing section, are solid particles and the nature of these particles depends on the quality of combustion. If combustion is poor, the carbon fraction in these particles is high and the size is somewhat larger. If combustion quality is very good, the particles are high in ash and salts and low in carbon and the particle size is considerably smaller.

Mechanisms which affect the capture of condensed particles in a condensing heat exchanger include:

1. Impaction (direct impact of particles on wet surfaces)
2. Interception (direct contact between surface and side of particles)

3. Diffusion (most important for smallest particles, can be enhanced by turbulence)
4. Thermophoretic enhanced diffusion (increased deposition due to particle motion driven by a temperature gradient)
5. Stefan flow (mass flux of condensing water toward heat exchanger surface)

Of these mechanisms the first two are most important for larger particles, over 1 micron, but become less efficient for submicron particles. To enhance particle capture by these mechanisms, impactors can be placed in the gas flow stream (e.g. tubes, water drops, or added fibers), gas velocity increased, and impactor size is reduced. Improving these inertial mechanisms generally requires increased pressure drop.

For mechanisms 3, 4, and 5, particle capture can be increased by increasing the surface area available for deposition, increasing the temperature gradient between the gas stream and the surface, increasing the mass transfer coefficient, and increasing the condensation rate (Butcher, Park et al. 1992, Butcher, Litzke et al. 1996).

Another approach that can be considered for enhancing particle removal is direct water condensation on the particles under supersaturated conditions. The degree to which this occurs is a function of the relative hydrophilic nature of the pollutants. High efficiency combustion will result in particles that are primarily inorganic salts and oxides (Chandrasekaran, Laing et al. 2011). These particles will be deliquescent and thus serve as effective condensation nuclei. Thus, there will be nucleation and growth of water droplets at relatively low supersaturation values leading to large droplets that can be readily removed from the stream. Thus, control of PM emissions from high efficiency wood burning systems should be an ideal application of condensing economizers to recover additional heat and supply a substantial measure of particulate matter control. However, the actual achieved particle capture will be a function of the heat exchanger design, condensation rate, water temperature, and combustion performance. The particulate capture of a condensing system can be enhanced by understanding the nature of the inlet particles, the heat and mass transfer coefficients in the exchangers, and the external conditions (gas flow and temperature, water inlet temperature and flow). Particle capture might be enhanced by reducing the inlet water temperature, reducing the flow passage size, adding water to the flue gas upstream of the heat exchanger section, using continuous sprays at the heat exchanger inlet, or potentially adding impaction surfaces such as woven plastic matrices within the heat exchanger passages.

The actual particulate removal efficiency which has been demonstrated in condensing economizers depends very much on the particle and heat exchanger conditions. Johnson et al. report on average 60% of the particulate matter of 1-2 microns and larger in size is removed and almost all particles larger than 5-10 microns are removed for an integrated flue gas treatment system condensing heat exchanger in oil and coal. However, the removal of fine particulates (less than 1 micron) has been limited to 50% or less (Johnson, Myers et al. 1995). Butcher et al demonstrated removal efficiencies from 80 to 98% with coal firing. With residual oil firing removal efficiency to 95% was demonstrated.

In several European studies, the particle removal efficiency of condensing heat exchangers with biomass-fired systems has been studied (IEA_Bioenergy 2011). One of the systems evaluated involved a carbon block heat exchanger (www.carbonizer.de). In several different tests with wood chips the mean particle removal efficiency was found to be 11%.

A residential, pellet-fired boiler is currently commercially available in Europe with a carbon, condensing heat exchanger. Tests of the particulate emissions from this unit with condensing "on" and "off" show a reduction with condensing on the order of 10% (IEA_Bioenergy 2011).

In a research project at the University of Eastern Finland (Gröhn, Suonmaa et al. 2009), a condensing heat exchanger optimized for particulate removal in biomass-fired systems was developed. The work included extensive modeling and was focused on residential, pellet-fired stoves. The optimized heat exchanger involved very small diameter tubes with laminar flow to optimize the diffusion and thermophoretically-enhanced diffusion mechanisms. A reduction in number concentration between 26 and 40% was reported across the heat exchanger. In further studies with a boiler system (Grigonyte, Nuutinen et al. 2014), mass removal efficiency of 32-36% was measured.

de Best, et al. (de Best, van Kemenade et al. 2008) did not explore the condensation of flue gas water but rather condensation of droplet-forming vapors directly within a heat exchanger. Very small diameter tubes, on the order of 2 mm were found to be needed to achieve high capture rates. An overall reduction in particulate emissions of 70% was reported. Fouling of heat exchanger surfaces by coarse particles is a concern.

In a companion part of this project, a pellet-fired boiler with a condensing heat exchanger was installed at Clarkson University. Details of the installed system are provided in the next section. The objectives of the work described here was to do an analysis of the potential for this heat exchanger to serve as a particulate removal device and to identify changes to the system that might be implemented to enhance particulate capture.

Description of the Target Boiler Plant and Heat Exchanger

The target installation for this work is a 150 kW (511,950 Btu/hr) output capacity pellet-fired boiler installed at the Walker Center of Clarkson University. The basic installation arrangement is shown in Figure 1, below. As shown, the system incorporates a thermal storage tank to enable longer operating periods of the boiler at its efficient, high load condition. This is a 500 gallon (1893 liters), well insulated tank, rated for operation at full system pressure.

The condensing heat exchanger shown in Figure 1 is a machined block graphite design. Test data was provided with this unit showing 91% particulate removal (mass basis) in tests done in Europe on a wood-chip fired commercial boiler. The system has been installed with a closed loop, recirculating chiller extracting heat from the condensing heat exchanger. This approach allows testing of this unit over a wide range of load temperatures. With a typical wood pellet at 6.2% moisture and a boiler operating excess air of 30% (15.5% CO_2), the flue gas mol fraction water vapor is 0.12 and the flue gas saturation temperature is 122 °F (50 °C). For condensing to be achieved, it is necessary for the cooling water to be below this and this is uncommon for the return water temperature from a radiator-type heat distribution system. The recirculating chiller provides the potential to explore a wide range of temperatures that could be realized with a different heat distribution system. This could include, for example, a radiant floor system.

It can be noted that heat pumps are used in combination with condensing heat exchangers in biomass-fired district heating plants in Europe. Analyses show favorable economics and efficiency (Hebenstreit, Schnetzinger et al. 2014). The heat pumps lead to strong condensation rates in the heat exchangers which reduces fouling and corrosion. Recovered heat is recycled back into the district heating system.

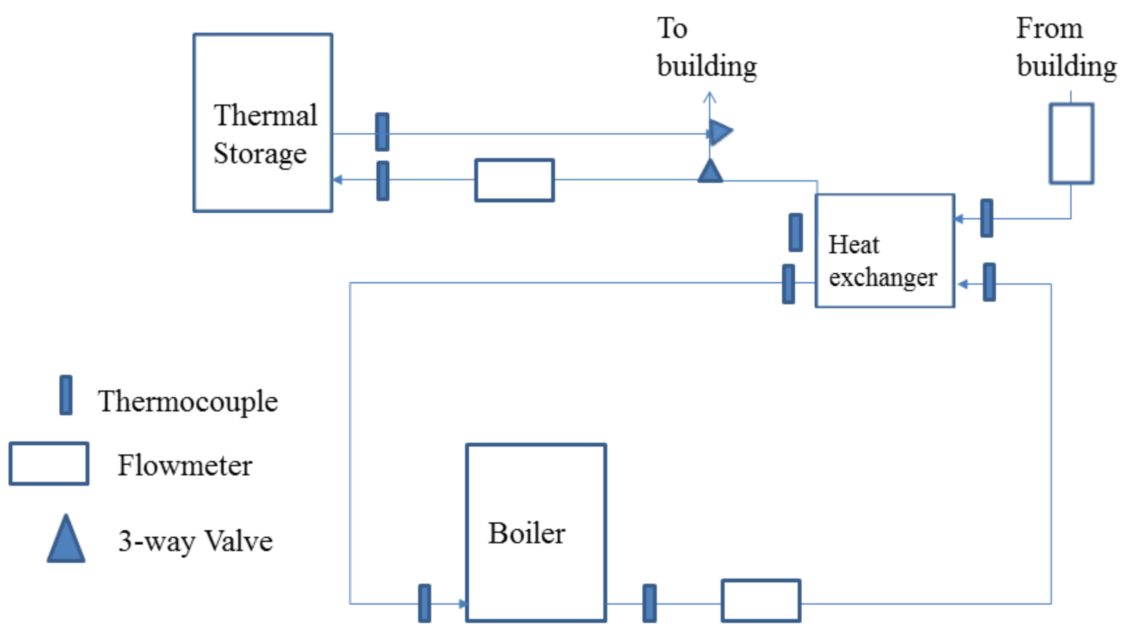

Figure 1 Basic arrangement of boiler installation at Clarkson

The boiler system at Clarkson is configured with a downstream cyclone for coarse particle collection (typically > 2 microns) followed by the condensing heat exchanger. There are induced draft fans located downstream of both the cyclone and the condensing heat exchanger. Figure 2 provides an illustration and includes some typical temperatures measured during operation.

Figures 3, 4, and 5 provide photos of the installed boiler, cyclone, and condensing heat exchanger respectively.

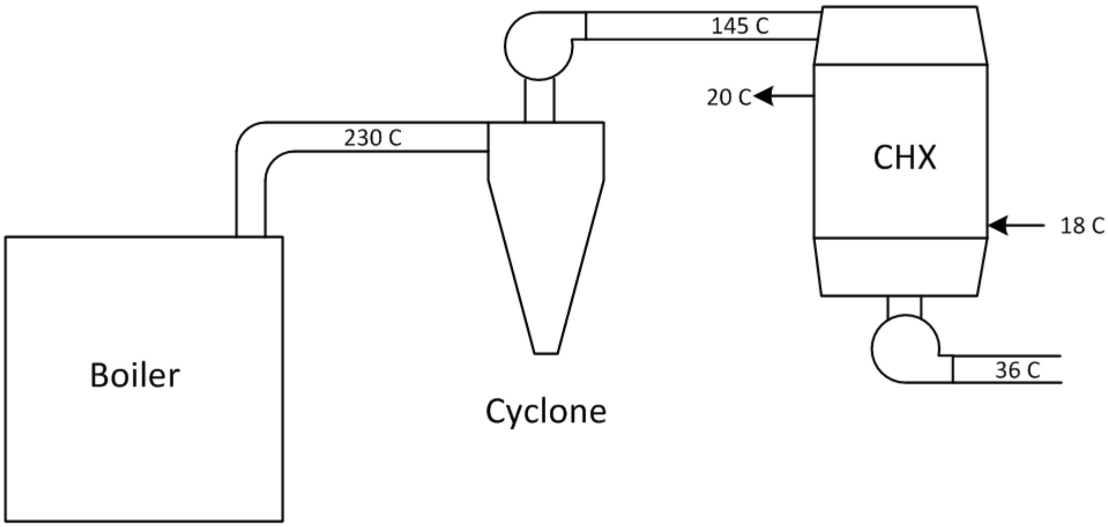

Figure 2 Test boiler installation at Clarkson University showing flue gas flow and typical temperatures

Figure 3 Boiler installation at Clarkson University

Figure 4 Cyclone dust collector installed at Clarkson University

Figure 5 Condensing heat exchanger installed at Clarkson University

Figure 2 shows a significant temperature decrease between the inlet and outlet of the cyclone. The cyclone and ducting are not insulated as shown in Figures 4 and 5, leading to this condition.

Figure 6 provides an illustration of the graphite block used in the heat exchanger construction. Advantages of graphite as a construction material include corrosion resistance and high thermal conductivity. The water flows horizontally through the drilled circular passages. The flue gas flows down through the non-circular passages. Figure 7 provides a more focused illustration of the cross-section of the flue gas flow passage.

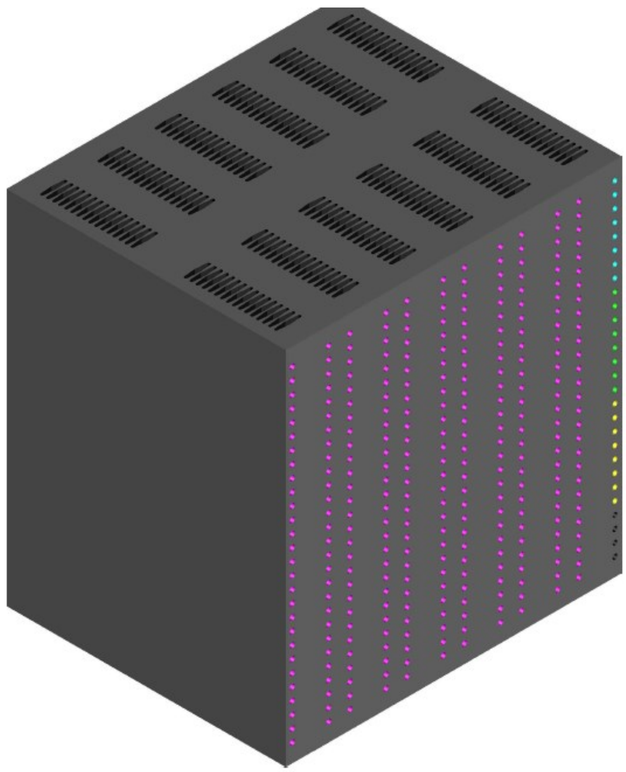

Figure 6 Illustration of graphite block used in construction of the condensing heat exchanger.

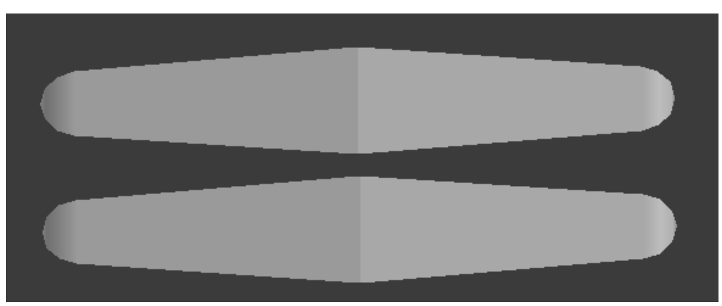

Figure 7 Illustration of the cross-section of the gas flow passages

On the gas side, the heat exchanger has 192 passages with a total cross section flow area of 74.3 in^2 (0.0479 m^2). The length of the gas flow passage is 23.6 inches (0.60 m). The hydraulic diameter of each flow passage is 0.445 inches (0.0113 m).

Analysis

At the full nominal output rate, the total flue gas mass flow, assuming 50% excess air, is calculated at 730 lb/hr (331 kg/hr). A basic heat transfer analysis in the heat exchanger was done assuming a flue gas entering temperature of 282 °F (139 °C) and a flue gas water mol fraction of 0.095.

The Reynolds number for the gas flow varies along the heat exchanger length but is well under 1000 indicating the flow is clearly laminar. Flue gas velocity is on the order of 8.2 ft/s (2.5 m/s). For this length of tube, the Graetz number is 14 and the flow is in a developing regime for the entire length of the heat exchanger. For these assumptions, Figure 8 shows the calculated temperature and mol fraction water vapor along the length of the heat exchanger. The graphite block (wall) temperature was assumed to be constant in this calculation.

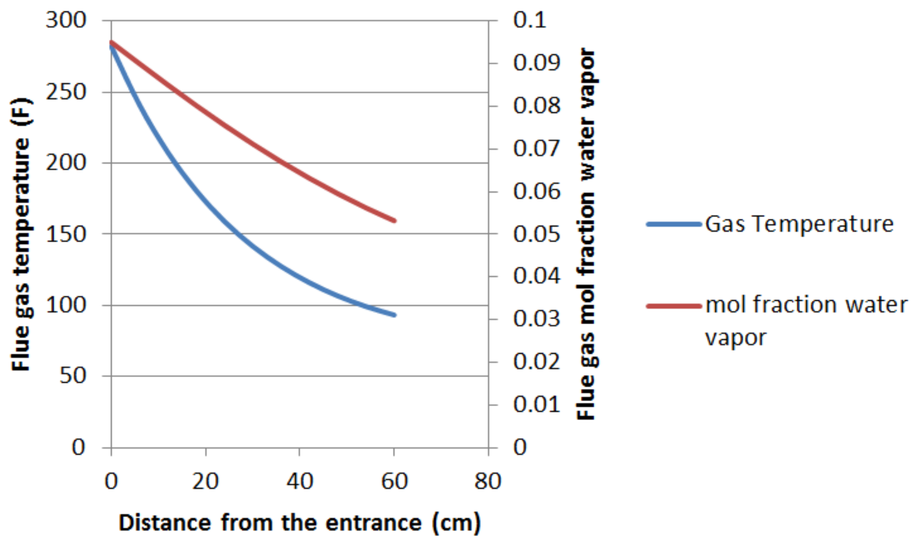

Figure 8 Calculated distribution of temperature and mol fraction water vapor along the length of the condensing heat exchanger

For this same case, Figure 9 shows the distribution of sensible and latent heat flux along the length of the heat exchanger and Figure 10 shows the water condensation rate.

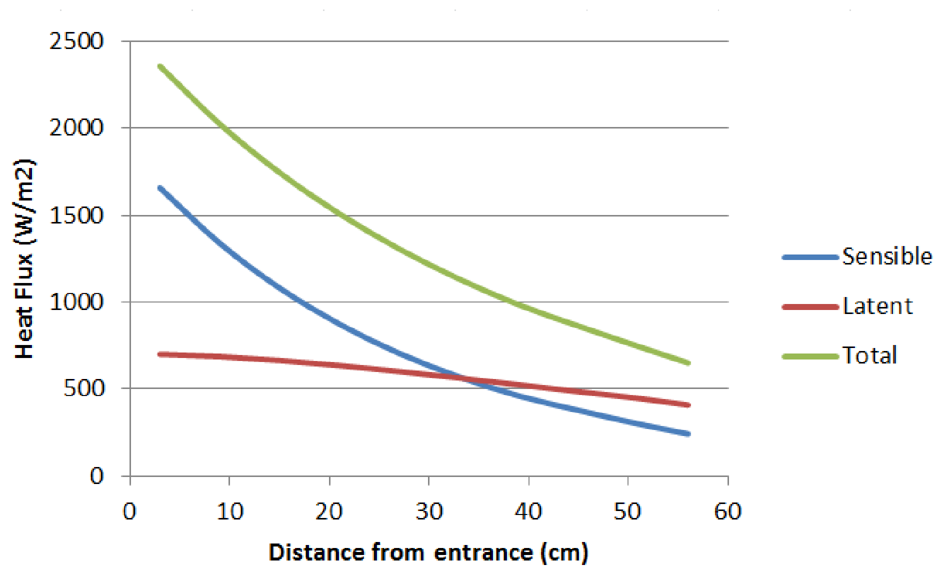

Figure 9 Calculated sensible and latent heat flux distribution along the length of the heat exchanger tube

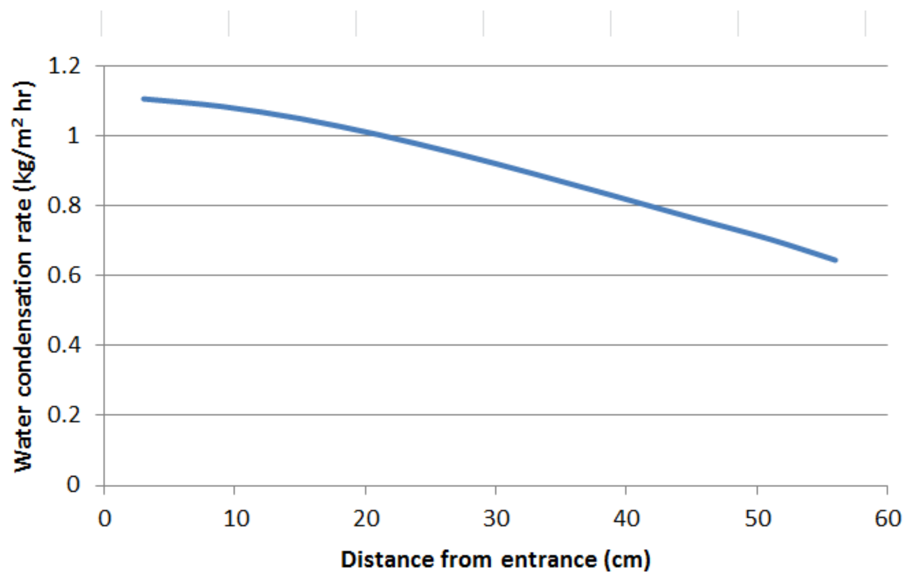

Figure 10 Calculated water condensation rate (kg/m^2 hr)

A CFD analysis of the sensible heat transfer and temperature distribution within one flow channel was done using ANSYS CFX. A laminar flow, 3D model was used based on the Reynolds number. Based on symmetry considerations, one quarter of the flow cross section was included in the analysis. Wall temperature was assumed to be constant and a range of assumptions were used in the analysis. The analysis was done over a range of cell densities. Because of the very slender configuration of the flow domain, a large number of cells was used. In the densest case, a nominal cell dimension of 0.01 inches (0.25 mm) was used with a total number of elements of 10 million.

Figure 11 shows for example one of the CFD results in the form of half-centerline temperature field. Overall the results show that, as a hot gas cooler, the effectiveness of this heat exchanger design is very high – in the 0.95 range.

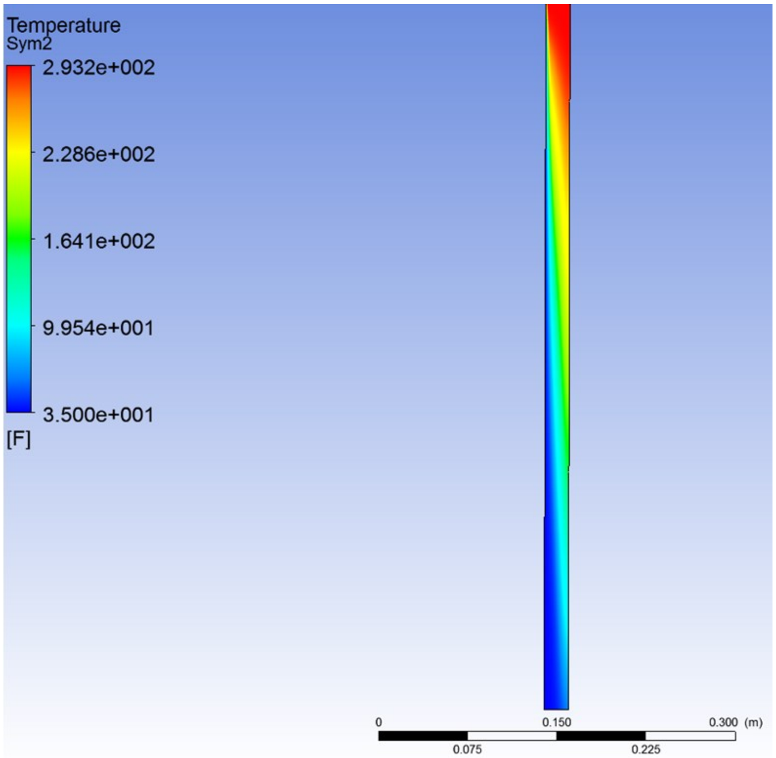

Figure 11 Example CFD results for temperature field on centerline. Left edge in image shown is the cold wall. Right edge is the centerline of the flow.

In considering the potential for particle capture in a condensing heat exchanger, an important starting point is the particle size distribution. The range of biomass combustion devices in use can be considered to span from dirty (high exhaust particulate concentration) to clean (low exhaust particulate concentration). Old-technology, cord-wood stoves and some outdoor wood boilers can be considered typical of the dirty technologies. The particulate emissions from these sources tend to be higher in carbon content and the particle size distribution is larger. Modern, wood pellet-fired stoves and boilers are cleaner. Particles from these sources are cleaner and the size distribution is shifted toward smaller sizes (Nussbaumer 2008, Chandrasekaran, Laing et al. 2011). This work is focused on modern pellet-fired boilers. The size range of interest for these boilers, for reducing the mass emission rate, is 50-500 nm (0.05 – 0.5 microns) (Johansson, Leckner et al. 2004, Grigonyte, Nuutinen et al. 2014). For this size range, capture of particles by inertial mechanisms and interception is likely to be insignificant (Butcher, Park et al. 1992).

For the specific geometry that is the subject of this work, the particle capture by diffusion has been estimated following the method of Willke and Baron (Willeke and Baron 2005) as presented by von der Weiden et al. (Von der Weiden, Drewnick et al. 2009). For a 100 nm particle, at the peak of the distribution, the capture efficiency is very low – 0.08%. Using the approach of Rosner (Rosner 1986), a multiplication factor for the effects of thermophoretic diffusion has been applied. With this, the capture efficiency for 100 nm particles is increased to 9.0%.

Recommendations for Enhancing Particulate Capture

Review and analysis in the prior section show that the expected capture of the fine particles produced in pellet combustion, with the geometry used in this installation is small and the primary mechanism for capture is diffusion enhanced by thermophoretic forces. In this section the potential to create supersaturated conditions within the flue gas, leading to particle growth for enhanced capture by downstream inertial mechanisms is explored.

An interesting analogy can be made between this approach and that used in a commercial aerosol sampler [www.aerosoldevices.com]. This product reportedly uses a three-stage condensation growth process to increase the size of solid particles from 5-10 nm to ~ 3 micron water droplets followed by inertial impaction for collection.

For the analysis in this section, it is assumed that the flue gas at the entrance to the condensing heat exchanger is at 293 °F (145 °C) and a mol fraction of water vapor of 0.095. As a first step, this is brought to saturation by adding water sprays. Assuming spray water at 35 °F (1.7 °C), the saturated gas after the spray section will be at 129 °F (54 °C) and a mole fraction of water vapor of 0.15. For this geometry and flue gas mass flow the water spray rate will be 0.058 gallons/min (0.22 liters/min).

In the condensing heat exchanger, the cool walls will not bring this to a supersaturated condition simply because the water vapor will diffuse to the walls faster than the gas will cool. Some particle capture enhancement with the sprays can be expected simply because of inertial impaction between the drops and the particles but this is expected to be small.

An approach for consideration to create a supersaturated condition is the mixing of very cold air with the now-saturated flue gas stream. Because of the location of this installation, this could involve simply mixing outdoor winter air with the gas stream. To illustrate this, calculations have been done assuming flue gas with 129 °F (54 °C) and a mole fraction of water vapor of 0.15. Two different cases are considered. In the first, the cold mix air is at 0 °F (-17.7 °C) and in the second the cold mix air is at 32 °F (0 °C). For both cases, the ambient air relative humidity is fixed at 70%. Calculations have been done over a range of ratios of cold mix air to flue gas mass flow. Results for the colder case are provided in Table 1 and for the warmer mix air case in Table 2.

Table 1. Analysis of Impact of Cold Air Mixing – Assumed Air Temp 0 °F (-17.7 °C)[1]

R^2	Mix Temp	mol fraction water vapor in mix	Saturation temperature of the mix	S^3	Air flow required
	°F (°C)	-	°F (°C)	-	scfm (m^3/min)
0.1	117.2 (47.4)	0.137	125.9 (52.2)	1.28	16 (0.45)
0.25	103.2 (39.6)	0.122	121.4 (49.7)	1.70	40 (1.13)
0.5	86.0 (30.0)	0.103	115.2 (46.2)	2.43	80 (2.27)

Table 2. Analysis of Impact of Cold Air Mixing – Assumed Air Temp 32 °F (0 °C)[1]

R^2	Mix Temp	mol fraction water vapor in mix	Saturation temperature of the mix	S^3	Air flow required
	°F (°C)	-	°F (°C)	-	scfm (m^3/min)
0.1	120.1 (49.0)	0.137	126.0 (52.2)	1.18	16 (0.45)
0.25	109.6 (43.1)	0.122	121.6 (49.8)	1.42	40 (1.13)
0.5	96.7 (35.9)	0.103	115.5 (46.4)	1.76	80 (2.27)

Notes (Both Table 1 and Table 2)

1. Other conditions for both tables: Gas entering is saturated at 129 °F (54 °C). Relative humidity of cold mix air is 70%.
2. Cold mix air/flue gas mass flow ratio.
3. Supersaturation ratio.

These results show that mixing cold air into saturated flue gas can create a significant degree of saturation with the potential for particle grow. There are, however, some important considerations. Of course, the approach will only work when outdoor temperatures are low, but these are also the conditions under which the biomass-fired boiler is expected to be running the most. This approach reduces the flue gas temperature and will significantly reduce the heat recovery in the condensing heat exchanger if the cold air is injected near the inlet to the heat exchanger.

Assuming success in growing the fine particles to a size range where inertial capture can be effective, it will be necessary to add a mechanism for this inertial capture. It is certainly feasible to add impactors such as woven plastic mats or to have additional water sprays just to provide such inertial capture sites. In an optimized approach, the heat exchanger could be moved upstream of the cyclone, with the water spray and cold air mixing downstream of the heat exchanger. With this approach the heat exchanger would primarily recover sensible heat but would still significantly improve the efficiency of the boiler. After the cold air mixing section, a wet cyclone could be used to capture the grown particles. Clearly this would require a major modification to the current installed equipment at the Clarkson University test site.

As a final consideration – cold air ducted in from outside would have to be conveyed in well insulated tubing to avoid heating across the warm boiler room.

Conclusions

This study has focused on an analysis of a specific condensing heat exchanger installed on a biomass (wood pellet) fired boiler in the Walker Center at Clarkson University. The goal of the analysis has been to evaluate particulate capture potential in the heat exchanger as installed, and to recommend design and operational changes that might be implemented to improve particle capture.

Overall the most significant capture mechanism for the fine particles produced with pellet combustion is thermophoresis enhanced diffusion. For the specific geometry installed at the Walker Center the total potential removal efficiency of the fine particles is about 10%. This is consistent with available published work on this topic.

To enhance particle capture, it may be possible to grow the particles and cold air injection into a flue gas stream saturated with water is proposed. Implementing this at the Walker Center with the current configuration would be difficult.

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