Dynamic Responses Analysis for Coal Fired Power Generation with Supercritical Units for Grid Code Compliance

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ABSTRACT

As a means to discover the best working conditions of supercritical coal fired power plants from a thermodynamic point of view, first simulations have been carried in order to reproduce the transition from compressed to supercritical water, passing through the pseudocritical point. A pipe with a 8.51 *mm* diameter and 1000 *mm* long wherein 100 $kg\ m^{-2}s^{-1}$ of water flows is heated up to produce a temperature increase from 350°C to 450°C. Preliminary design has been undertaken in order to estimate the necessary heat flux, and the results have been transferred to a program where a CFD module has simulated the different behaviour for several thermodynamic properties. The results obtained fit the expected trends, although the pseudocritical point is achieved further along in the pipe. Additional research is necessary in to investigate higher mass fluxes.

INTRODUCTION

The UK's power generation sector is in transition from a well-balanced mix of coal, nuclear and gas-fired power stations to one in which the old nuclear and coal-fired stations will be progressively retired in exchange of new nuclear and renewable energies. However, new nuclear power stations will take a long time to be ready, with the earliest estimated time of construction not expected to be until 2018. On the other hand, renewable energies have a slow rate of development, and they are very unlikely to be capable of generating enough electricity by themselves to fulfil the power requirements of the UK [1]. These facts coupled with projected economic growth have caused the Office of Gas and Electricity Markets to state that the generation capacity of electricity might fall from 14% in 2012 to 4% in 2015/16 [2].

Looking for an abundant energy source in the interim to offset this energy gap, one inevitably looks towards coal, which happens to be the most abundant fossil fuel in terms of world-wide reserves, and also very widespread [3]. In China, back in 2011 they consumed almost as much coal as the rest of the world together [4]. Its availability makes its price less prone to sudden fluctuations as other power plant fuels and as a result, companies like RWE Npower and E.ON have planned new coal-fired power stations to be built in the UK in the near future.

At the same time, and due to fossil fuel emissions contributing significantly to climate change, new environmental policies are becoming stricter and forcing the introduction of new environmentally-friendly technologies to reduce the amount of CO_2 released to the atmosphere. To this end, the British government has committed to an 80% reduction in emissions by 2050 compared to the 1990 levels. In order to meet the various requirements in electricity demand, environmental emissions, finance, and performance, coal-fired power generation has adopted a series of cleaner and more efficient technologies. In these cleaner coal technologies (CCTs), improving energy conversion efficiency has been one of the most important development directions, in addition to carbon capture and storage.

One of the available CCTs that can achieve high efficiency without jeopardising the environmental impact takes place in a supercritical coal-fired power plant (SCCFPP). This technology is based on increasing the water pressure inside the boiler pipes beyond the critical value of water. Inside the supercritical water (SCW) cycle, the supercritical state commences in the water wall (WW) pipes surrounding the furnace, where the combustion occurs. Compressed water (at pressures ranging from 29 to 30 *MPa* and temperatures between 250°C and 350°C) enters the WW from the bottom and increases its temperature as it flows upwards. When the fluid reaches the critical temperature (374.1°C) the supercritical state is gained instantaneously and water becomes a non-condensable, monophasic fluid. As the SCW keeps on being heated, at a certain temperature above the critical value the pseudocritical (PSC) point is achieved and the thermodynamic properties experience a very sensitive behaviour, so for instance the density drops and the heat capacity peaks in only a few degrees. At this moment, the SCW becomes a highly compressible steam-like phase, with improved thermal behaviour with respect to the carriage of heat and no required latent heat of vaporisation. Therefore, the overall thermal efficiency increases. The fluid leaves the WW at outlet conditions around 27-28 *MPa* and 450-500°C. Table 1 shows a comparative summary of the operative conditions in conventional (subcritical) and SC technologies:

	Subcritical (conventional)	Supercritical
Temperature (°C)	500 – 550	500 – 600
Pressure (*MPa*)	16 – 17	24 – 26
Operation	Drum, constant pressure	Once-through, sliding pressure
Cycle Efficiency (%)	33 - 35	42

Table 1: Comparative summary of Coal-Fired Power Plant Operations

The three main operational advantages in SCCFPPs are:

- Compared to the traditional subcritical power plants, pressure-increased supercritical power plants will improve the plant energy efficiency up to around 10% (absolute).
- Once through (OT) operation: as it is a monophasic fluid, there is no condensation and hence no separation is required. This simplifies boiler design as the drum employed to store saturated steam and water in conventional power plants is no longer necessary.
- Flexible operation characteristics: as opposed to constant pressure operation in conventional power plants and thanks to the OT operation, SCW boilers are designed to operate under variable or ‘sliding’ pressure conditions, allowing SCW to respond to changes in pressure gradually. This reduces the thermal stress in the high-pressure turbine, shortens start-up times and allows faster response to changes in the boiler load.

However, the SCCFPP still faces reservations in the UK. The relatively small scale of the UK electricity network has forced the National Grid Code (NGC) to be far more demanding than other European countries to make up the lack of a bigger, more stable system. This grid stability is maintained thanks to power plants working on "dynamic frequency response" mode, modifying their power output (electricity pulses) when changes in power demand make frequencies surpass the +/- 0.5 *Hz* tolerance range in a 50 *Hz* system.

The strictest NGC regulation states that, if a sharp power demand triggers a grid frequency drop equal to or bigger than - 0.5 *Hz* (1% of the nominal system frequency, 50 *Hz*), the power plant would have to successfully activate the "primary response capability (P)" between 10 and 30 seconds after the drop, increasing the overall power generation by 10% in that time.

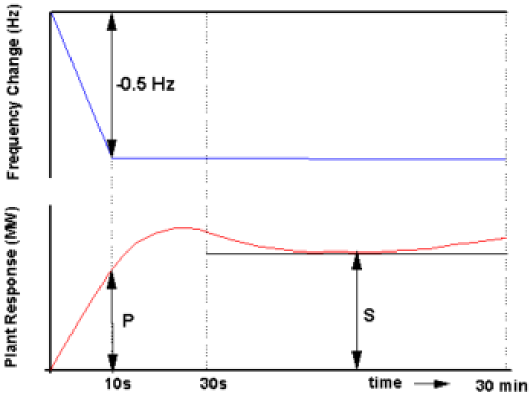


Figure 1: Mandatory Primary and Secondary Frequency Responses in Power Plants.

In a subcritical boiler, this requirement is achieved thanks to the boiler drum providing operational flexibility and rapid frequency responses, as it stores energy that can be released by opening the outlet valve on the drum, increasing the steam expansion in the turbines and enabling a rapid frequency response to comply with the primary response criteria.

Supercritical boilers achieve high efficiencies thanks to the higher pressure values over the entire OT-operating water cycle, as there is no integral steam drum; however, they subsequently suffer from a lack of stored energy, and although they can modify the working pressure easily, they respond quite slowly when facing the need for a fast increase in turbine output during steep increases in power demand. As a result, it is currently not known whether or not the SCCFPP dynamic responses could satisfy the GB Grid Code requirement [5].

To install this CCT in the UK, there is a need to better understand how their best dynamic responses can be achieved at sudden changes in energy demand. Proper fluid flow and heat transfer studies are of the essence for a better understanding of the boiler dynamic responses alongside control strategy; however, at present, there are no supercritical boilers operating in the UK. Comparatively, there are more than 400 SCCFPPs worldwide, and China operates more than 22 of them, so a strong collaborative research partnership has been developed between the University of Warwick (UK), University of Birmingham (UK), Tsinghua University (China) and North China Electric Power University (NCEPU). In the University of Warwick, a large scale thermal power plant modelling and simulation research laboratory has been set-up jointly with the Tsinghua University, and a complete mathematical model has been developed.

At the University of Birmingham and due to the limitations of using SCW under laboratory conditions, simulation-based research is being undertaken, focusing on the thermodynamic behaviour of SCW flows, both in response to sudden changes in working conditions such as heat flux and mass flux, and at different geometric configurations of furnace piping (i.e., vertical, horizontal, inclined). This information cannot be easily obtained from an operating plant. Special interest lies around the PSC zone, where the properties vary the most with small temperature changes. Through these analyses, the heat transfer quality produced by forced convection will be evaluated, in terms of heat transfer coefficient and thermal efficiencies.

The obtained data will be then experimentally verified by the operation of laboratory apparatus using a modelling fluid (CO_2) working at supercritical conditions that will allow the measurement of temperatures along the pipe and produce heat transfer calculations based on real data. Additionally, a novel approach to energy storage as an alternative to a conventional drum in a power plant will be investigated, both in terms of potential operational solutions, and engineering design.

As a whole, the best working conditions from a thermodynamic point of view will be identified for a SCCFPP, and more accurate models of heat transfer will be created in order to enable better control models and more efficient furnace designs to be produced.

MATERIALS AND METHODS

The first goal is to simulate and verify experimentally a horizontally-oriented heated test element (pipe) wherein a compressed fluid flow reaches the supercritical state and surpasses the PSC conditions. In practice, WW pipes are usually oriented in an array such that the water flows diagonally upwards, and even though the initial simulations and experiments will be focused on horizontal configurations to establish a base case comparable to some existing data [6-9], one of the study's final targets is to obtain results from inclined configurations (from 0° to 90°) in order to obtain an angle-resolved evaluation of heat transfer efficiency.

When performing simulations for the test element with SCW, a temperature range between 350°C and 450°C has been set. For design purposes, a constant pressure of 30 *MPa* was chosen, as the pressure drop along the test element was initially considered negligible. This implies that the thermodynamic properties at these conditions depend only on the temperature values, and can be easily obtained from the NIST database [10].

With respect to the experimental validation, the equivalent conditions for the supercritical CO_2 ($SCCO_2$) were obtained through consideration of the reduced temperature and reduced pressure (see equations (1) and (2)), producing an equivalent pressure of approximately 10 *MPa* and an equivalent operational temperature range from 20°C to 67°C.

$$\boldsymbol{T_R = \frac{T}{T_C}} \tag{1}$$

$$\boldsymbol{P_R = \frac{P}{P_C}} \tag{2}$$

Inversely, a mass flux range from 1800 to 4000 $kg\ m^{-2}s^{-1}$ was firstly chosen for the $SCCO_2$ rig, and then scaled up to the SCW simulation, producing a range from 1653 to 3673 $kg\ m^{-2}s^{-1}$.

Preliminary design was necessary both in simulation and the consideration of the experimental apparatus in order to have an initial, simplified idea both of the required heat flux applied on the test element and of the form that the axial temperature profiles of the element would take. The global energy balance in the system can be described as:

$$\dot{q}_{IN} = (Energy)_{OUT} - (Energy)_{IN} = W_m \cdot (\overline{u_2} - \overline{u_1}) \qquad (3)$$

Where $(\text{Energy})_{\text{IN}}$ and $(\text{Energy})_{\text{OUT}}$ refer to the energy flows entering and leaving the pipe respectively, $\dot{\boldsymbol{q}}_{\text{IN}}$ is the inlet heat rate in $J\ s^{-1}$, W_m is the mass flow in $kg\ s^{-1}$ and $\bar{\boldsymbol{u}}_{\boldsymbol{2}}$ and $\bar{\boldsymbol{u}}_{\boldsymbol{1}}$ are the outlet and inlet specific internal energies respectively at the specified conditions, in $J\ kg^{-1}$. This equation, for every value of mass flow rate (obtained through the fixed mass flux and the pipe cross-sectional area) produced the heat rate required to heat up the pipe in the selected temperature range. By specifying the pipe length, heat fluxes were likewise calculated.

A differential analysis was performed in order to obtain an equation that showed the temperature profile inside the pipe at stationary conditions:

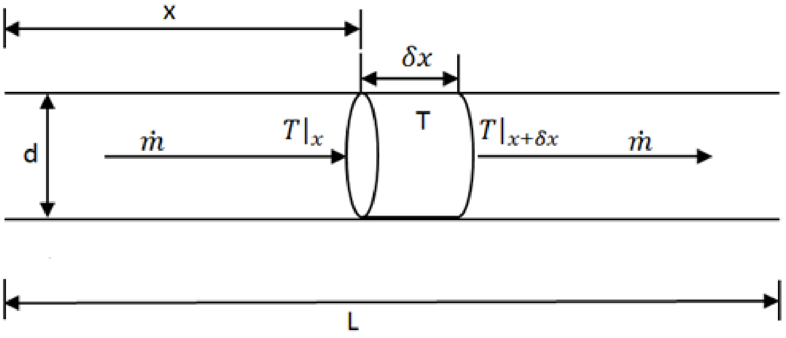


Figure 2: Differential analysis of a heated pipe section.

The fig. 2 represents a pipe with diameter d and length L, wherein a mass flow $\dot{\boldsymbol{m}}$ enters a volume element of thickness δx at a position x and at a temperature $T|_x$. A heat rate is applied on this element, and therefore the outlet temperature of the flow increases to $T|_{x+\delta x}$. The following assumptions were made:

- The flow in the pipe is turbulent and thus the volume element has a flat velocity profile.
- Instantaneous radial heat transfer occurs due to this velocity profile.
- There are no frictional momentum losses, and thus process can be considered isobaric.

The equation obtained relates the temperature value, through heat capacity, at every point of the pipe with dimensionless length:

$$\frac{x}{L} = \frac{W_m}{\dot{q}_{IN}} \cdot \int_{T_{IN}}^{T_x} C_P \cdot \partial T \qquad (4)$$

Where x is a point from 0 to L (in *m*), L is the total pipe length (in *m*), T_x and T_{IN} are the inlet temperature and the temperature at the chosen point, and C_P is the heat capacity of the fluid at the chosen conditions.

The results obtained from the preliminary design were then utilised as a starting point for simulations in Comsol Multiphysics®, a finite-element solver for many different disciplines. The computational fluid dynamics (CFD) module is one of them, and offers the possibility to work with different turbulence models at non-isothermal conditions. The procedure involves several steps, which include definition of physics, system geometry, system materials, process parameters and variables, the specification of steady-state or transient conditions, and the configuration of a suitable mesh in order to solve the equations. An important issue that arose was the fact that the software's predictions for the thermophysical properties of water at supercritical conditions were not available, so the material "SCW at 300 *bar*" had to be created by specifying the thermodynamic properties, as multi-fitted piece-wise polynomials in order to overcome the high sensitivity at the PSC point.

Similarly, the initial calculations provided the parameters to start designing the $SCCO_2$ rig, where compressed CO_2 is led to a cooler and stored in a "hydraulic/pneumatic piston accumulator" in order to pump the CO_2 uniformly. Before entering the test element, it is preheated and when passing through the test element reaches and surpasses the critical state by means of a heat source around the pipe. Unfortunately, the $SCCO_2$ rig is currently still in development and thus there are no results on the experimental validation so far.

RESULTS

The differential analysis produced the profile shown in figure 3. The plot depicts the PSC point (401.9°C at 300 *bar*) occurring at half of the pipe length, and the temperatures present the same location in the pipe regardless the mass flux considered (as the higher the mass flux, the higher the heat flux required to achieve the same temperature increase).

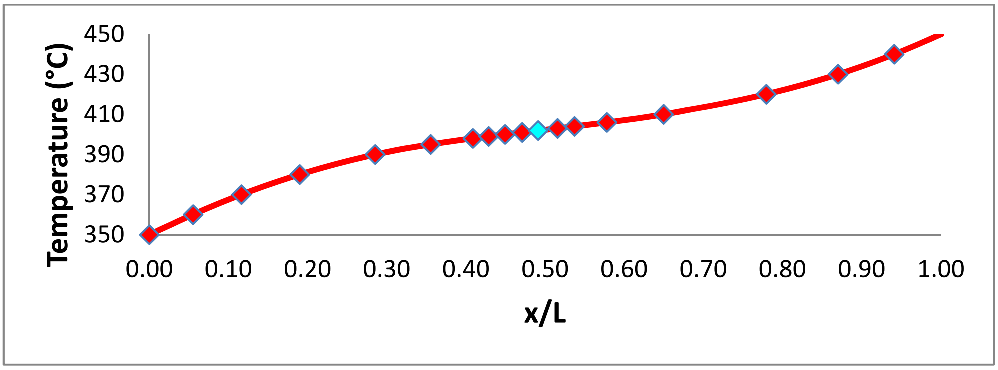
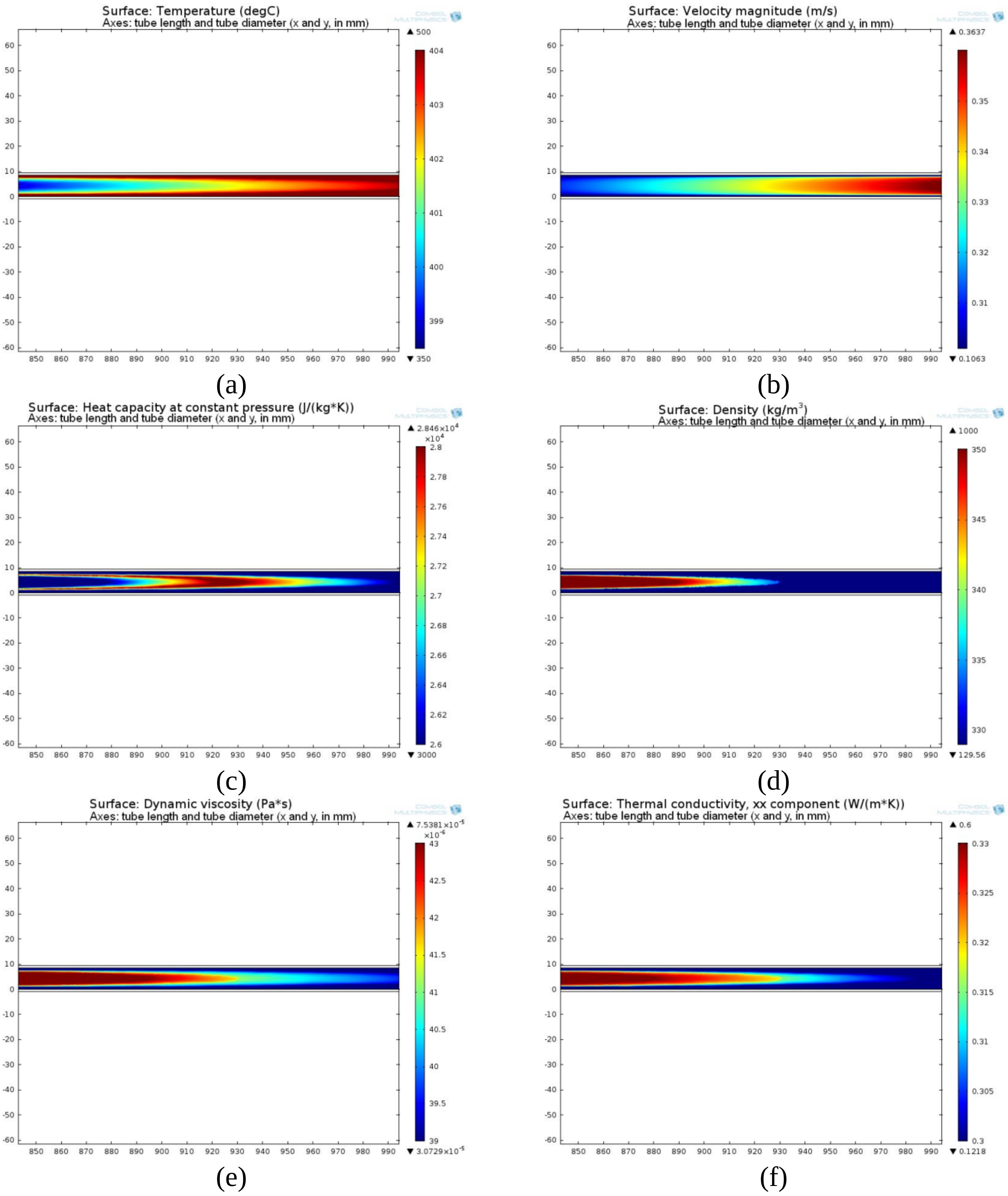


Figure 3: Temperature profile along the heated pipe section for SCW.

Simulations of SCW at 300 *bar* have been performed in 2D in Comsol. Although still in the turbulent regime, low flow velocities have been successfully computed. In this case, for a pipe with an inner diameter of 8.51*mm* and a length of 1000 *mm*, at a mass flux of 100 $kg\ m^{-2}s^{-1}$ and a heat flux of 258 $kW\ m^{-2}$, the resultant transition to the supercritical (PSC) regime and the subsequent effect on various thermophysical properties is presented in figure 4.



(a) (b)

(c) (d)

(e) (f)

Figure 4: Thermodynamic profiles for various properties of SCW at 300 bar flowing at 100 kg $m^{-2}s^{-1}$. (a) Temperature, (b) Linear velocity, (c) Heat capacity at constant pressure, (d) Density, (e) Dynamic viscosity, (f) Thermal conductivity.

The graphs in Figure 4 have been selected in order to specifically show the values near the PSC range. The PSC temperature (401.9°C, figure 4(a)) fully develops in the bulk fluid at values close to 930 *mm*, which is much further along than the expected 500 *mm* estimated on the first calculations (x/L=0.5). This is very likely to be due to the simplifying assumption that the heat transfer only occurred axially and not radially. The velocity profile (figure 4 (b)) shows good agreement with the value at the PSC point (expected around 0.3 $m\ s^{-1}$) although the outlet velocity differs with the calculated value because of the PSC point appearing much later than expected in the flow. The thermodynamic properties occurring at PSC conditions (Figure 4(c)-(f)) show a good fit with the NIST database, which confirms the computation applied the polynomials adequately. The heat capacity plot is of special interest, as it depicts clearly the peak expected when approximating the PSC range.

However, when trying to simulate at higher values of mass flux, the simulation suddenly fails after a series of iterations. The reasons are not quite clear yet, although is likely to happen due to the coupled effect of the increasing mass flow and the decreasing viscosity (mostly appreciated near the PSC point), which produces a dramatic, local rise of the turbulent regime and might collapse the iterations. Turbulence parameters such as the turbulence intensity and the turbulence length scale might have to be adapted to these sensitive conditions. Alternatively, it has been observed on the model that providing a temperature value on the pipe outer surface rather than a heat flux reflects a better behaviour of convergence, so it might be worthy of further research.

CONCLUSION

The first simulation results on SCW at 300 *bar* fit the expected behaviour quite well, although the PSC point was achieved further along than expected along the pipe, which indicates the necessary amount of heat flux should be higher than the estimated.

Attempts to simulate SCW flow at higher mass fluxes than 100 $kg\ m^{-2}s^{-1}$ have been unsuccessful, and therefore further research is necessary in order to fully understand the process and obtain more robust results in 2D before taking the next step to 3D simulations.

REFERENCES

[1] HUHNE, C., Speech to Centre Forum**. 2011**.

[2] MAYOR K., MOKKAS S., Electricity Capacity Assessment (Office of Gas and Electricity Markets), **2012**.

[3] McMULLAN, J. T., WILLIAMS, B. C., McCAHEY, S. Energy Policy, Vol. 29, **2001**, p. 441.

[4] U.S. Energy Information Administration - International Energy Statistics.

[5] NICHOLLS R.J., C. MAXIM. E.ON UK. **2008.**

[6] WITHAG, J.A.M. *et al.,* The Journal of Supercritical Fluids, Vol. 70, **2012**, 156–170.

[7] SALLEVELT, J.L.H.P. et al., The Journal of Supercritical Fluids, Vol. 68, **2012** 1– 12.

[8] KIM, D. E, KIM, M., International Journal of Heat and Fluid Flow, 32, **2011**, 176–191.

[9] JIANG, P-X. *et al*., International Journal of Heat and Mass Transfer, 51, **2008**, 6283–6293.

[10] LEMMON E.W., McLINDEN M.O., FRIEND D.G. "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, http://webbook.nist.gov, (retrieved March 31, **2014**).