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EXPERIMENTAL STUDY AND SIMULATION ON HEAT EXPOSED LIQUID FILLED PROCESS EQUIPMENT

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ABSTRACT
Heat exposure of process equipment is a complex problem area that has gained interest over the last years. The reason is that existing standards vague on the subject and operate with too low heat load compared to what has been found in experiments. It has also been shown that the subject is more complex than expected when the existing standards were formed. It has been clear lately that simple formulas will not cover all the aspects and variation of the phenomenon. It seems that multi physic simulations are needed to be able to predict the behaviour satisfactorily. VessFire is such a simulation system that can handle this problem and has been widely used the last years by several companies and projects.

One of the major parameters that need to be modelled is the heat transfer phenomenon inside the equipment shell. This is a difficult task and it is not easy to find data for verification.

This paper describes a number of experiments performed for verification purposes. The project was supported by The Petroleum Safety Authority Norway and is a result of the authorities' need for better means in safety management as new technology is introduced. The simulation results show good agreement to the experiments and indicate that the simulation system gives a reasonably good representation of the phenomena.

INTRODUCTION
The Petroleum Safety Authority Norway (PSA) has sponsored the project presented in this paper. The project part 1 started in 2002 and part 2 and 3 continued in 2003/4. The project's name is 'Heat Exposure of Process Equipment'.

Norwegian state organization of petroleum activities.

We would like to say a few words about how the Authorities are organized in Norway, concerning petroleum activities. As far as management of petroleum resources, and safety and working environment are concerned, the Norwegian Petroleum Directorate (NPD) was the governmental body up to January 1. 2004.

From January 1 2004 the NPD was split in two, and the Petroleum Safety Authority Norway (PSA) was established. The PSA is now the governmental body in safety issues, issuing regulations and taking care of the daily regulative and supervisory functions. The PSA is subordinate to the Ministry of Labour and Social Affairs.

Expectations to the project.

Petroleum activities have taken place on the Norwegian Continental Shelf for more than 30 years. From the beginning fire and explosion has been one of the main concerns of the authorities, due to the nature of the products processed on the installations.

The authorities have for several years been aware that different standards give various recommended heat loads on process equipment. Despite substantial research, agreement on a standardized fire load has not yet been reached.

The objective of the project 'Heat Exposure of Process Equipment' part 1, was to answer the question; 'What is a relevant heat load, and how should it be modeled?' Evaluation of available codes was also a part of the project.

A report from this project was issued in December 2002. This report revealed some new areas that needed further research activities, and part 2 of the project was launched. Key issues here are heat transfer between materials, liquids and gas. A report from this project was issued in December 2003. The objective of part 3 was to establish a link between the fire itself and the exposed process equipment. A complete model should be developed that could show the effect from a fire on the exposed component in an interactive process. To perform further research work into this subject, a part 4 will most likely be launched in 2005. The objective is to integrate structural strength into the model.

Control Philosophy. Performance based regulation.

It is important to emphasize that the Norwegian HSE regulations for petroleum activities are performance based rather than being prescriptive [7]. The regulations are supported by guidelines, and the guidelines describe methods of achieving the functional requirements and goals. Normally the guidelines refer to international and national standards. It is therefore important for the regulator to know which standard is the most relevant, concerning for instance fire technical issues. This is why the PSA in Norway is supporting this project.

Requirements for protection of process equipment against fire.

Requirements to fire protection of process equipment are stipulated in Regulation relating to design and outfitting of facilities etc. in the petroleum activities section 28.This section say: 'Where passive protection is used, it shall be designed so as to give relevant structures and equipment adequate fire resistance with regard to load bearing properties, integrity and insulation properties during a dimensioning fire.' In the guidelines it is further stated that: 'for gas and liquid-filled vessels and pipe-sections, the passive fire protection should be sufficient to prevent rupture before depressurisation is carried out.' The relevant standard referred to in this section is NORSOK S-001. This standard has the following heat flux values:

Type of fire	Initial heat flux Max. point loads	Initial heat flux density Average load
Pool fire (crude) Open or enclosed area Fuel controlled	150 kW/m^2	100 kW/m^2
Pool fire enclosed area Ventilation controlled	200 kW/m^2	130 kW/m^2
Jet fire	250 kW/m^2	

New platform concepts – new challenges for safety management.

During the last years we have been introduced to new concepts for developing oil and gas fields in Norway. This concerns mostly developments in deep-water areas, deeper than traditional developments (70-150m). The petroleum activities are also moving further north on the Norwegian continental shelf. Northern areas imply more harsh weather conditions, and also environmental concerns.

It is therefore of importance to have good competence and knowledge in the HSE-area when developing new fields. The design must be based on well-proven and well-documented technology. But the performance-based regulations are also an opportunity for the operator to develop other technical solutions with the same safety level as those described in the guidelines, as long as compliance with the required safety level can be documented. To do this, applying new technology or deviate from traditional solutions, requires highly qualified design resources. This includes both personnel and design tools. The 'Regulation relating to design and outfitting of facilities etc. in the petroleum activities section 8, stipulates the following requirements concerning qualification and use of new technology and new methods: 'Where the petroleum activities involve use of new technology or new methods, criteria shall be prepared with regard to developments, testing and use in order to fulfil the requirements to health, environment and safety. The criteria shall be representative of the relevant operational conditions, and the technology or the methods shall be adapted to already accepted solutions.

Qualifications or testing shall demonstrate that applicable requirements can be fulfilled by use of the relevant new technology or new methods.'

THE TECHNOLOGICAL CHALLENGE

In a process plant there is a range of different components such as vessels with different kinds of inventory, different types of valves, pipes, tubing, pumps, turbines, heat exchangers, etc. All have their specific safety related aspects when exposed to fire.

The main safety issue when process equipment is exposed to fire is to prevent escalation of the accidental situation. Fire in a process plant usually implies that an accident already has taken place. The purpose for the remaining process equipment is then to maintain integrity and moderate the effect of the accident.

Most materials will loose their strength as the temperature increases. A logical strategy is then to reduce mechanical load on the equipment. Depressurization system is a well-known mean in the process industry and is normally a standard part of a process plant. The aim of a blowdown system is to reduce the pressure inside the process equipment faster than the strength reduction due to heat exposure. As fire is most probably fed from the process itself the purpose of the blowdown is also to reduce fuel supply to the fire. The challenge is to design the equipment and the system to have the required property.

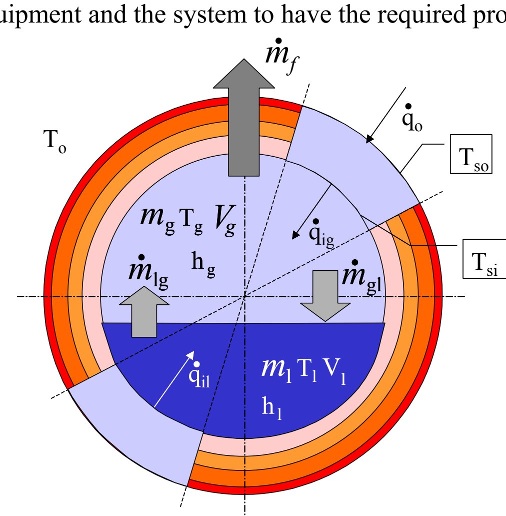

Figure 1 Overview of the physical processes in a blowdown situation, including heat exposure, for liquid filled equipment.

Figure 1 shows an overview of the physical processes that govern the blowdown process. Assuming a fire, the heat exposure on the outside is dependent on convective and radiative heat transfer to the shell. The heat transfer to the outside is dependent on the flow situation around the shell and the emissivity and absorptivity properties of the shell material. The shell surface temperature is influenced by the conductivity of the shell material and the heat transfer inside the shell surface. As the inside shell surface is contact with both liquid and gas in addition to a splash zone, the heat transfer conditions are quite complex. Some standards reject heat transfer to the gas zone with the argument that the heat transfer coefficient to gas is significant less than to liquid. This is an erroneous argument for two reasons. At high pressure the heat transfer coefficient increase significantly. Even if less heat is transferred, the density of gas is significant less than liquid and the temperature increase of the gas might be a main contributor to the pressure increase.

When liquid is heated it evaporates. The evaporation process is dependent on pressure, temperature and composition of the liquid and gas. Gas can also condense. In addition there is a convective heat transfer between the liquid and gas zone that must be considered. The surfaces in the gas zone also radiates from the shell to the liquid.

During the blowdown process mass is usually evacuated from the gas zone, but also liquid might be released. The rate of release is dependent on density and pressure as well as the release area.

As pressure and temperature change, the properties of all materials change. This has to be considered in a prediction of a blowdown process.

The main purpose of a blowdown process is as earlier stated to maintain integrity of the equipment. The strength properties of the shell are the key factor on that matter. The strength is dependent on the inside pressure as well as the support forces. If the exposing forces produce stress that exceeds the ultimate tensile stress (UTS) in some regions, the integrity of the equipment is no longer maintained. In the design phase of a process plant, these aspects are crucial and must be included as a dimensional factor. For that reason prediction of the blowdown process is essential.

Lately some new standards has been introduced to the industry on this matter [3] and [4].

VessFire [1] and [2] is a multi physics system designed for calculation of this kind of problems. It has been applied for some time in the oil and process industry on many projects. The system satisfies the requirements for predictions outlined in [3] and [4]. It includes all aspects described above including integrity of the shell. As part of the verification process some experiments where performed. Some of the experiments are presented here.

EXPERIMENTAL STUDY

The purpose of the experiments was to investigate the evaporation process and the heat transfer to the liquid and vapour. In a complex system it is important to reduce unknown parameters as far as possible. Exposure from a flame is difficult to control. Flux measurements are point values and not necessarily representative for the average exposure. In order to control the heat exposure it was decided to apply an electric heating system. The system and the verification of the system is described in [5], [6] and [8].

The furnace was built inside a supporting tube. Figure 2 shows a general arrangement of the experimental outfit. A 0.05 mm stainless steel foil formed as a tube, 300 mm in diameter, generated the heat. The power supply was based on a 3-phase alternating current system giving 48 Volt output as maximum. The top exposure had a limit of 300 kW. The foil had a surface of about 1 m^2, giving a heat flux up to 300 kW/m^2. The power input could be continuously regulated from zero to maximum load. Each experiment was started from zero and brought up to the required load within a few seconds. After that the surface temperature of the heating foil was kept constant during the exposure period. Experiments with both dry objects as well as water filled object were performed. In this paper only water filled experiments are presented.

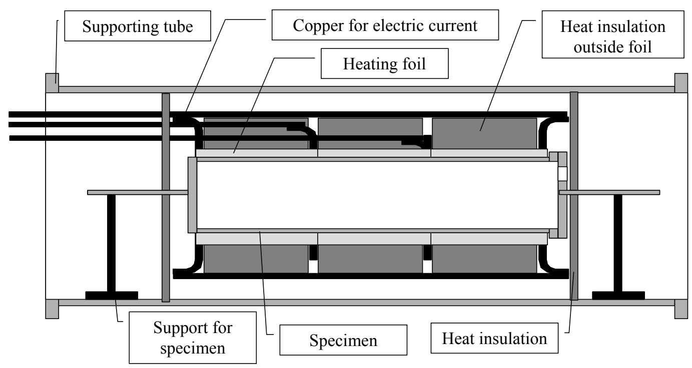

Figure 2 **General arrangements drawing of the experimental furnace including the specimen and its support.**

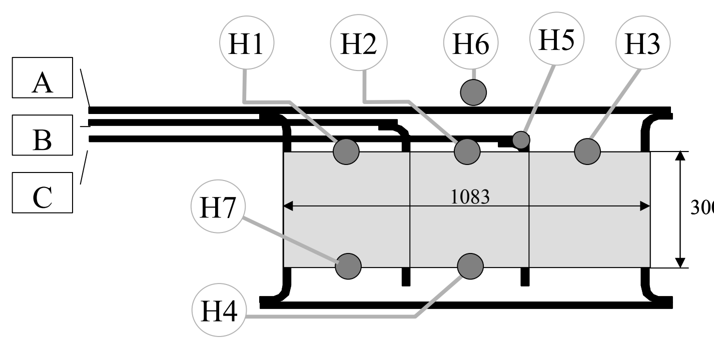

Figure 3 **Illustration of the heating unit. The black part is copper conductors for the foil. The grey part is the heating foil exposing the specimen. The foil is equipped with thermo-elements all marked H, except H5 which is the temperature in a copper ring and H6 which is the temperature between the insulation and the supporting tube.**

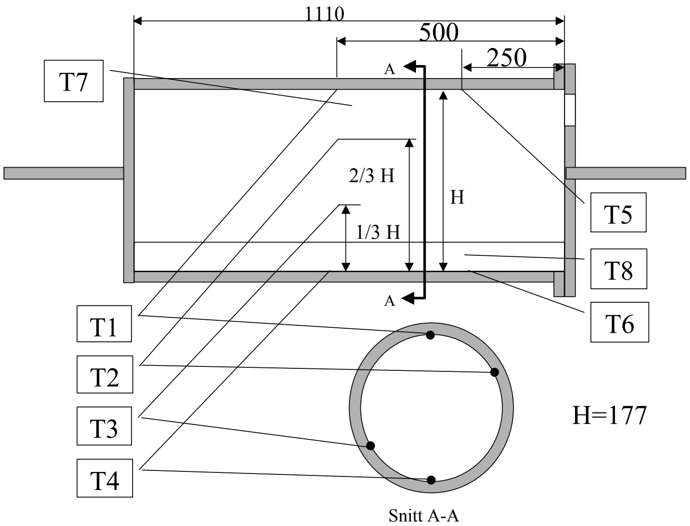

Figure 4 **Illustration of the specimen exposed for heat (not in scale). The locations of temperature measurements are marked with T. All measures are in mm. T7 is the temperature in air (vapour phase) and T8 is temperature in water when applied.**

Figure 4 shows the instrumentation of the test specimen (test object). The wall of the specimen was 12.5 mm thick. The temperature was measured by 1.5 mm thermo-elements of K-type. The location is shown in the figure. In some experiments water was filled into the specimen and boiled dry.

Several tests were performed with different heat loads and different filling of water inside the specimen. These are reported in [5] and [6]. In this presentation three cases will be presented. The characteristics for these cases are:

Experiments	Foil temperature [°C]	Initial water content [kg]
Case 1-03	900	2.98
Case 2-03	900	1.5
Case 4-03	1000	2

Case 1-03

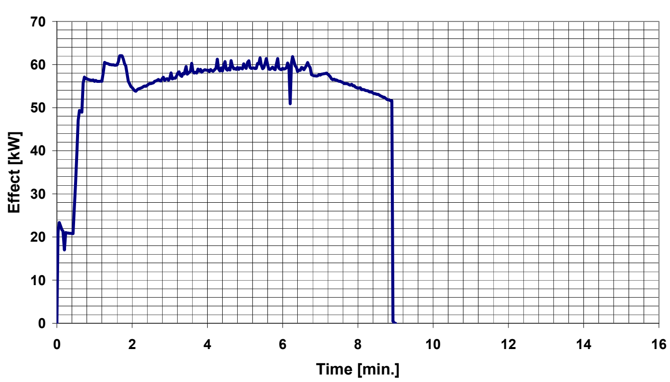

Figure 5 **Measured effect input to the heating foil during the experiment case 1-03.**

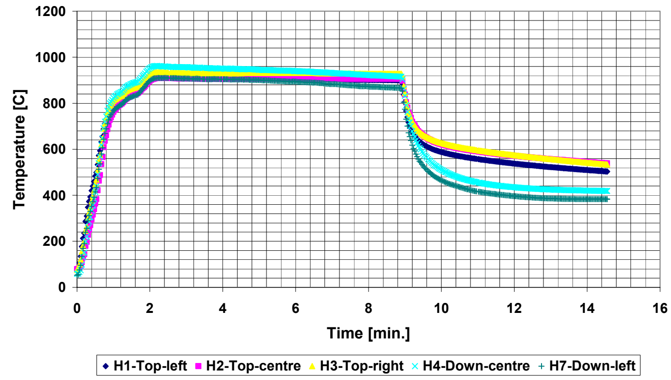

Figure 6 **Measured temperature of heating foil for case 1-03. The legend refers to Figure 3.**

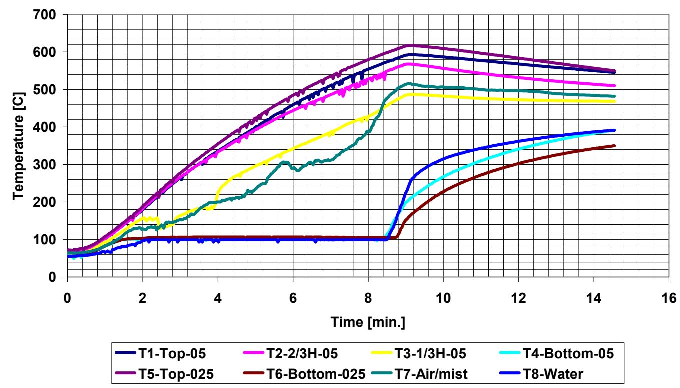

Figure 7 **Temperature on specimen during test case 1-03. Legend refers to Figure 4. Thermocouple T8 is measuring water temperature until all water is evaporated.**

Case 2-03

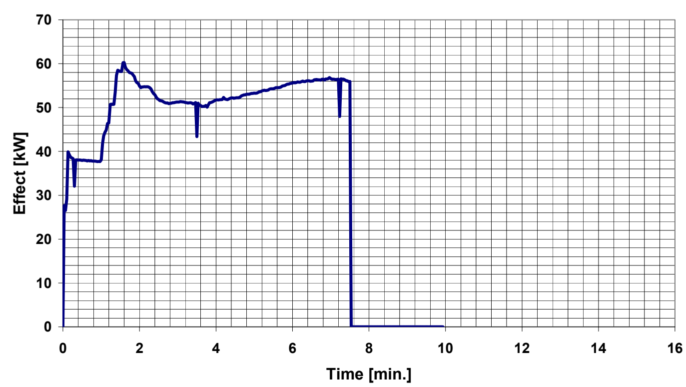

Figure 8 **Measured effect input to the heating foil during experiment case 2-03.**

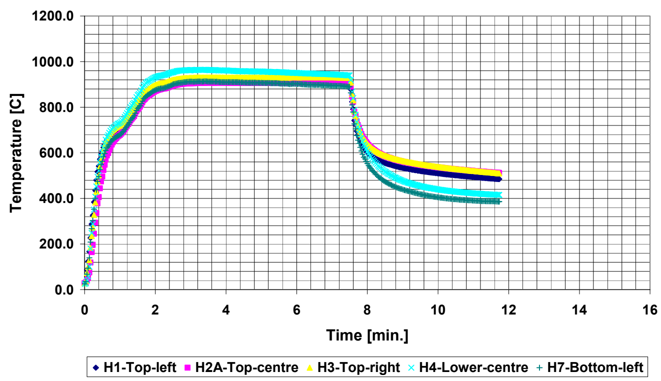

Figure 9 **Temperature of heating foil during test case 2-03. Legend refers to Figure 3.**

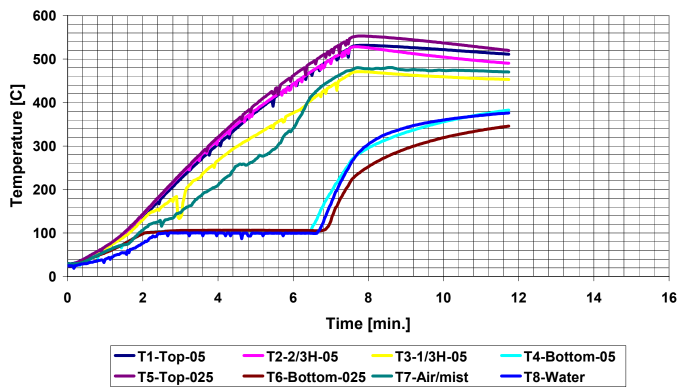

Figure 10 **Temperature of specimen during test case 2-03. Legend refers to Figure 4. Thermocouple T8 is measuring water temperature until all water is evaporated.**

Case 4-03

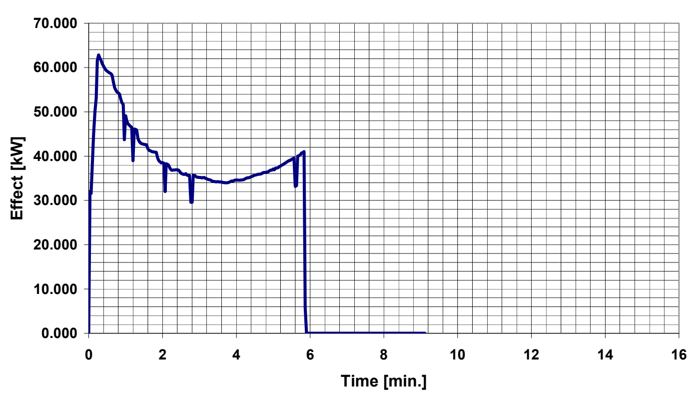

Figure 11 **Measured effect input to the heating foil during experiment case 4-03.**

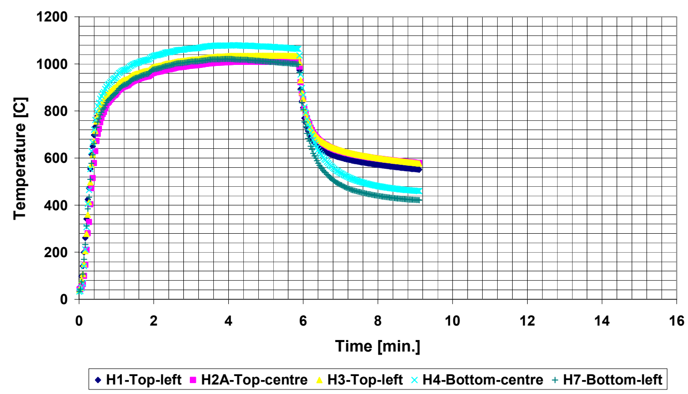

Figure 12 **Temperature of heating foil during test case 4-03. Legend refers to to Figure 3.**

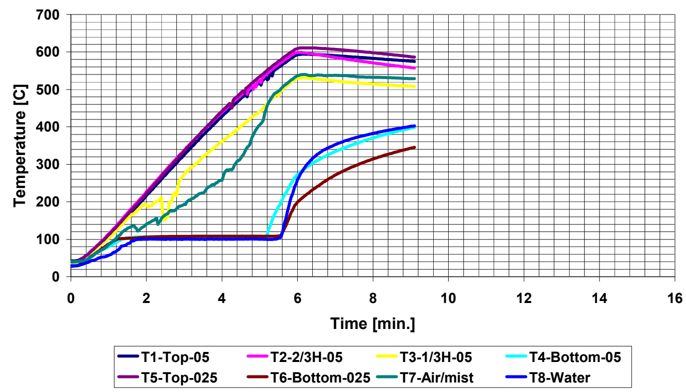

Figure 13 **Temperature of specimen during test case 4-03. Legend refers to Figure 4. Thermocouple T8 is measuring water temperature until all water is evaporated.**

SIMULATION STUDY RESULTS

Simulations have been performed using VessFire. This is a system for simulation of fire response of process equipment. It simulates heat conduction and performs stress calculations of a 3-dimesional shell. Simultaneously the system simulates the inventory by treating the gas phase and liquid phase separately. The two phases are linked through evaporation, condensing, heat transfer and evacuation (for blowdown simulations). The whole system is linked together to a multi-physics simulation. See [1] and [2].

VessFire is assuming exposure from a flame in kW/m^2. In general the flux can vary in time and space, but in this case the heat load is constant in space. The heat flux includes both radiated heat and convective heat and is defined to be the net flux transferred to the exposed object while the object is at its initial conditions. Figure 14, Figure 17 and Figure 20 show the heat load applied in VessFire for the different cases. The load is found by taking the average measured temperatures of the heating foil and apply the Stefan-Boltzmann law. The simulations assume the inventory gas zone initially to be filled with air, 78% N2 and 22% O2. The emissivity of the specimen is set to 0.7.

Figure 15, Figure 18 and Figure 21 show the results of measured and calculated inventory temperatures. When thermocouples are used to measure gas temperatures there is a risk of having influence from the surrounding temperatures. In this situation the surrounded steel was glowing and obviously influenced the thermocouple by radiation. This is in general a problem and should be noticed when results are published. The influence can be quite strong and is here estimated by using the calculated gas temperature to calculate a corresponding thermocouple temperature. In the figures this is called "Calc. temp. thermocouple". The calculation is done stepwise by use of:

$$\frac{m_t c_p \Delta T}{\Delta t} = Q_c + Q_t$$

where ΔT is the temperature increase during the time Δt, m_t is the mass per m and c_p is the specific heat for the thermocouple (Inconel). The convective heat transfer is calculated as

$$Q_c = h_t A_t (T_l - T_t)$$

$$h_t = 0.2673 \frac{\lambda}{d_t} Nu \cdot \mathrm{Re}^{0.33}$$

where A_t is the surface area of the thermocouple per m and T_l and T_t is the temperature for gas and thermocouple respectively. λ is the thermal conductivity for the actual gas and d_t is the outer diameter of the thermocouple. Nu and Re is respective the Nusselt and Reynolds numbers.

The net radiation heat transfer is calculated as

$$Q_s = \frac{A_t \sigma (T^4{}_s - T_t{}^4)}{\frac{1}{\varepsilon_t} + \frac{A_t}{A_s}\left(\frac{1}{\varepsilon_s} - 1\right)}$$

where A_s is the area of the enclosing specimen per m, $\varepsilon_t = 0.3$ is the emissivity thermocouple (Inconel), $\varepsilon_s = 0.7$ is the emissivity for specimen inside and σ is the Stefan-Boltzmann constant for black radiation. T_s is the specimen temperature on the inside.

The correction is an estimate, but it gives an idea of the magnitude of the influence on the thermocouple from the specimen surface.

Figure 16, Figure 19 and Figure 22 show the comparison between the measured and calculated steel temperatures. They also show the time where all the water is evaporated. The steel temperature at the bottom of the specimen remains constant as long as there is water present. When the steel is dry the temperature increases rapidly. As can be seen from the figures the boiling time is reasonably well predicted and so are the steel temperatures.

Case 1-03

Initial water content: 2.98 kg.

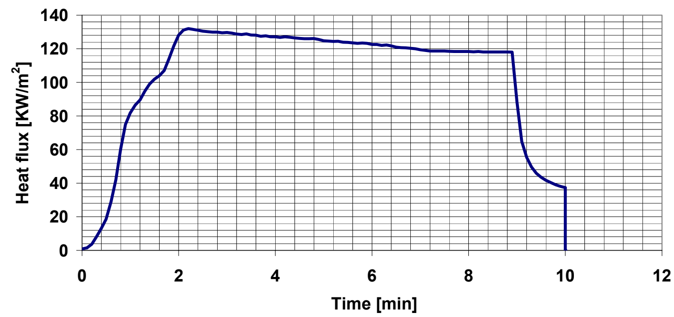

Figure 14 Heat load applied in VessFire for case 1-03.

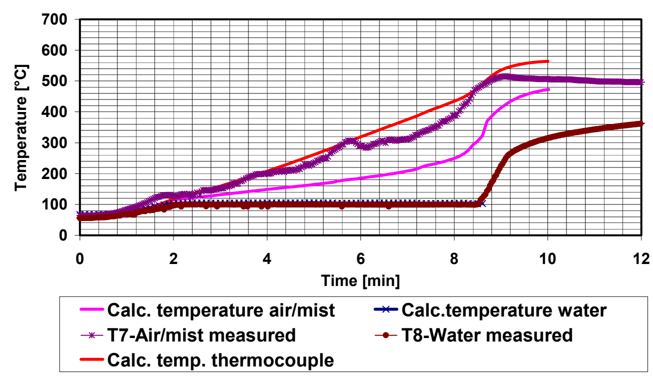

Figure 15 Inventory temperature of air/mist and water case 1-03. The calculated thermocouple temperature is based on simulated temperature. Legend refers to Figure 4.

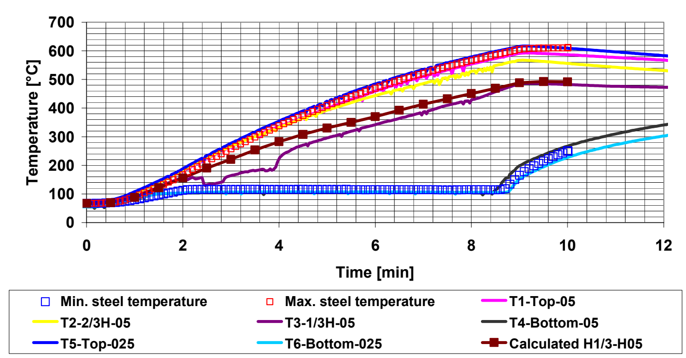

Figure 16 Calculated and measured temperatures of the specimen steel for case 1-03. Legend refers to Figure 4.

Case 2-03

Initial water content: 1.5 kg.

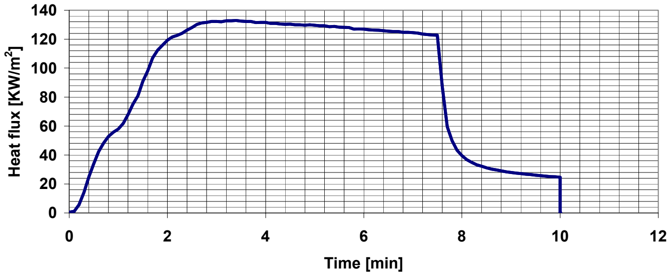

Figure 17 Heat load applied in VessFire for case 2-03.

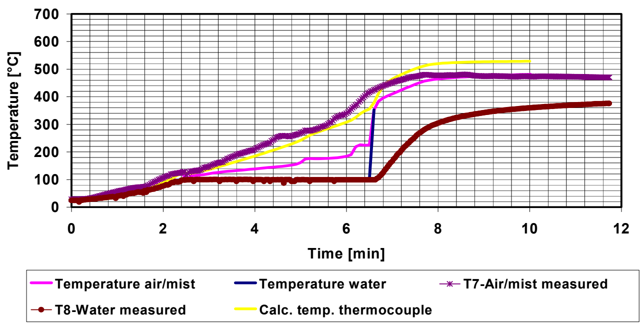

Figure 18 Inventory temperature of air/mist and water case 2-03. The calculated thermocouple temperature is based on simulated temperature. Legend refers to Figure 4.

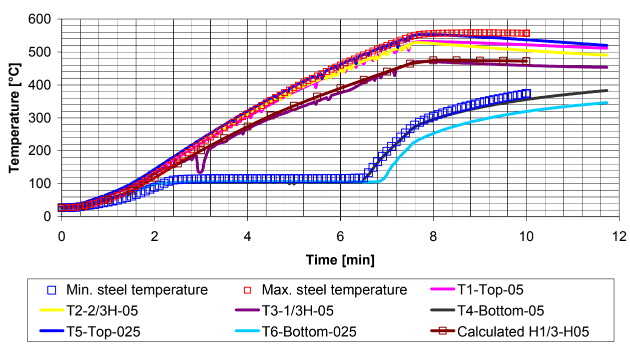

Figure 19 Calculated and measured temperatures of the specimen steel for case 2-03. Legend refers to Figure 4.

Case 4-03

Initial water content: 2. kg.

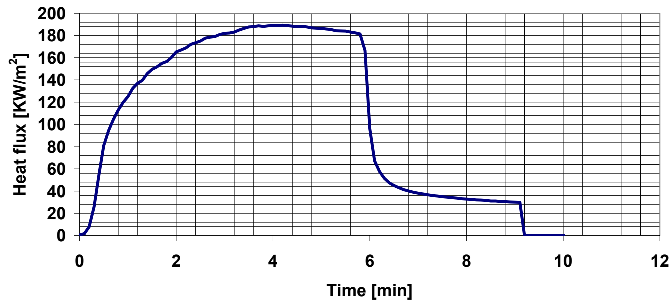

Figure 20 Heat load applied in VessFire for case 4-03.

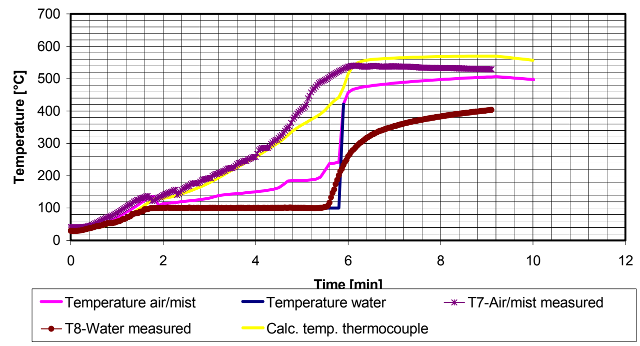

Figure 21 Inventory temperature of air/mist and water case 4-03. The calculated thermocouple temperature is based on simulated temperature. Legend refers to Figure 4.

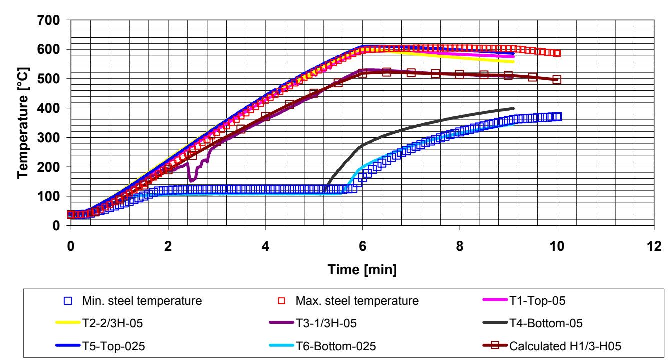

Figure 22 Calculated and measured temperatures of the specimen steel for case 4-03. Legend refers to Figure 4.

CONCLUSION

The aim of the experiments was to gain data on heat transfer in process equipment for comparison to simulation results. Water was used as inventory medium. The specimen used was an 8" carbon steel pipe closed in one end by welding and flanged in the other end. The heat was supplied by an electric heating system consisting of a cylindrical formed steel folio.

A single heat transfer coefficient is not possible to come up with as a coefficient will vary both for the liquid and vapour phase as well as for both phases in the splashing zone. The key parameters to verify against are therefore the time temperature curves for liquid, vapour phase and steel temperatures. But probably the most important parameter is the time when all water is evaporated. The specimen was not quite horizontal and this is indicated by the difference in time for temperature rise in the thermocouples located in the steel covered by the water. But the difference in time is not significant. The results give a good indication on the evaporation time.

It can be concluded that the simulation results from VessFire is in general in good agreement with the experiments. The heat transfer seems to be reasonably represented by the system.

ACKNOWLEDGMENTS

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