Heat flux in jet fires

Unified method for measuring the heat flux levels of jet fires

Reidar Stølen
RISE Fire Research
Trondheim, Norway
reidar.stolen@risefr.no

Ragni Fjellgaard Mikalsen
RISE Fire Research
Trondheim, Norway
ragni.mikalsen@risefr.no

Karin Glansberg
RISE Fire Research
Trondheim, Norway
karin.glansberg@risefr.no

Espen D Wormdahl
RISE Fire Research
Trondheim, Norway
espen.wormdahl@risefr.no

Keywords: jet fire, heat flux, standardisation, testing

Abstract:

Passive fire protection materials are used to protect critical structures against the heat from fires. In process plants with pressurized combustible substances there may be a risk of jet fires. Through risk analysis the severity of these jet fires is determined and these result in fire resistance requirements with different heat flux levels for different segments. The relevant test standard for fire resistance against jet fires does not include any measurements or definitions of the heat flux in the test flame which the tested object is exposed to. This paper presents methods for reaching different heat flux levels and how to measure them in a jet fire with limited deviations from the established jet fire test standard.

Introduction:

Jet fires are ignited leakages of pressurized liquid or gaseous fuel. In jet fire testing for the offshore industry, heat flux is the defining factor for the accidental loads. NORSOK S001 [1] defines two different heat flux levels of 250 kW/m^2 and 350 kW/m^2 depending on the leak rate of hydrocarbons. These heat flux levels are used in risk analysis and define what type of fire load bearing structures and critical equipment need to be able to resist in a given area. Examples of such ratings can be "250 kW/m^2 jet fire for 60 minutes", "350 kW/m^2 jet fire for 15 minutes" or any other combination based on calculations in the risk assessment. Combined with critical temperatures in the tested object this defines the performance criteria for the passive fire protection. Each configuration of the passive fire protection needs to be tested and verified. Manufacturers of passive fire protection request fire tests to document their performance against jet fires with these various heat flux levels. The relevant test standard for determining the resistance to jet fires of passive fire protection materials is the ISO 22899-1 [2]. This test standard has been developed as a laboratory-scale fire resistance test that aims to simulate some of the thermal and mechanical loads that has been observed in larger scale jet fires. The test standard describes a propane jet with 0.3 kg/s into a re-circulation chamber as shown in Figure A. However, this test standard does not define any heat flux level or any method to define or measure it.

RISE Fire Research has developed a method for defining and measuring the heat flux levels in jet fires. This method can be used when faced with the challenge of testing passive fire protection against specific levels of heat flux. The method includes a custom test rig that allows jet fire testing with different heat flux levels, including those specified by NORSOK S001. A large number of tests have been performed at the test facility of RISE Fire Research in Trondheim, Norway.

In this paper, the method will be presented. Assessments and choices made in the development of the method will be emphasized, to encourage discussion amongst stakeholders in the industry. The goal is to establish a unified measurement and calculation method.

Experimental set-up:

The proposed test setup and procedure to reach the specific heat flux levels are in many ways equal to the ISO 22899-1 standard for jet fire resistance testing [2]. Propane is used as fuel with a rate of 0.30 kg/s. The fuel is released towards the test specimen from a nozzle with the same dimensions and nozzle position relative to the test specimen as described in ISO 22899-1.

The main difference compared to the existing standard is the design of the flame re-circulation chamber. To reach high temperatures, the chamber is enlarged. Increased size of the re-circulation chamber increases the compartmentation of the jet flame, and thereby increases the temperature inside the chamber, compared to the ISO 22899-1 standard chamber design. The wall surfaces of the re-circulation chamber reflect and re-emit radiation in the compartment. This effect can be compared to the thermal exchange with an open larger flame that extends further than the dimensions inside the compartment. The same effect is used in the rear wall of the standard jet fire setup according to ISO 22899-1, where the warm steel plate behind the test specimen is simulating the radiation from a long flame from a larger gas jet release that extends far beyond the impinged object. This is an effect that can be used to simulate larger fires using smaller propane release rates.

The internal dimensions of the standard re-circulation chamber are 1.5 m · 1.5 m · 0.5 m. Typical internal dimensions of the modified re-circulation chamber are 2.6 m · 3.0 m · 3.0 m. The test specimen can either replace the rear wall (e.g. panel specimen) or be placed inside the re-circulation chamber (e.g. tubular section specimen). The ISO 22899-1 re-circulation chamber and the enlarged chamber for high temperatures are illustrated in Figure A and Figure B.

Nordic Fire and Safety Days (NFSD2018) Conference proceedings (with peer-review), pp xx-xx, Published by RISE Research Institutes of Sweden, DOI xxx-xxx-xxx,, 7-8 June 2018, Trondheim, Norway

Figure A: Design of the re-circulation chamber according to ISO 22899-1 [2].

Figure B: Enlarged re-circulation chamber for high temperature jet fire testing. The bricks supporting the nozzle inlet are the same dimensions as in Figure A, enabling scale comparison.

Another modification compared to the standardized test setup is the addition of temperature measurements in the flame. These temperatures are measured with 1.5 mm encapsulated K-type or R-type thermocouples, positioned within an 8 mm tube, which is sealed at the end. Other thermocouple geometries have also been used, but the tube geometry has been found to be most suited, as will be discussed below.

The thermocouples are placed within the re-circulation chamber. Normally 6 flame temperatures are measured, in the lower, middle and upper part of the chamber. Thermocouples should be positioned mid-flame (i.e. away from the chamber wall and test specimen), in the lower, middle and upper part of the chamber.

Results and Discussion:

Choice of measurement system: Heat flux is defined as the flow of heat through a surface. The heat flux from a fire to an engulfed surface of an object depends on both the engulfing flame and the properties of the surface. The properties of the surface may change during the exposure to the flame as it heats up and changes its surface properties. At some point the object inside the flame will reach a thermal equilibrium with the flame where the net flow of energy into the object is balanced by the energy emitted from the object. The heat flux for an object can be calculated as incident heat flux, emitted heat flux or net heat flux. A definition of heat flux needs to include parameters of the receiving object. These variations give a lot of degrees of freedom when calculating heat flux in a fire.

Heat flux can be measured directly, using a heat flux meter. For jet fire tests, however, this has been found not to be feasible. Special water cooled gardon gauge heat flux sensors are designed to measure heat flux to a cooled surface, but these have proved to be very unreliable when placed inside a high temperature jet fire test. In a test series of five tests, four different gardon gauge heat flux sensors were placed inside the re-circulation chamber of the high temperature jet fire test setup. The heat flux sensors were calibrated against an electrically heated furnace before and after each of the tests. The sensitivity of the sensors was measured to be able to account for changes during the test period. The calibration results showed that the sensitivities of the sensors in mV / W/m^2 changed between -97% and +90% during the tests making the use of the measurement data very unreliable.

This indicates that the gauges have been influenced or damaged permanently by the environment inside the flame. Formation of soot during the tests on the cold surfaces of the gauges can be one of the reasons for the changed properties. Similar challenges are also reported in [10] where a method of purging the surface of the heat flux sensors with nitrogen was used to reduce the problem with soot deposits on the heat flux sensors.

A more robust and easily defined method is to measure the equilibrium temperature inside an object placed inside the flame. This is the principle used in plate thermocouples (Figure C-right) used in fire resistance furnace testing [3]. In our experience, these plate thermocouples are often heavily damaged during high temperature jet fire tests. This raises questions on how long into the tests such measurements are reliable. Other types of objects have been tested, such as a cube thermocouple, consisting of a 40 mm sides steel cube, with a thermocouple inside (Figure C-center). The advantage of such a cube is that it has a higher heat capacity and gives less fluctuating measurements. It also has a longer heating time and can be used to quantify the net thermal energy that is absorbed by an initially cold object during the first few minutes of the fire. Another type is a small 8 mm steel tube, which has been sealed in the end and has a thermocouple inside (Figure C-left). Compared to the cube thermocouple, this gives a quicker thermal response.

Figure C: Thermocouple systems used in jet fire tests. Tube thermocouple (left), cube thermocouple (center) and plate thermocouple (right).

One representative high temperature jet fire test has been selected to visualize the difference between the use of tube and cube thermocouples (plate thermocouples are not displayed due to malfunction in such tests), see Figure D. In this test, a total of eight tube thermocouples (K and R types) and two cube thermocouples were placed in an enlarged re-circulation chamber to measure the flame temperature. Tube thermocouples were placed in the lower, middle and upper part of the chamber on both sides of the jet fire center point. The cube thermocouples were placed in the upper part of the chamber, near the two topmost tube thermocouples. As seen in Figure D, a faster initial response is observed for the tube thermocouples compared to the cube types. Starting from about 13 minutes until the end of the test, the two types of thermocouples measures similar average temperatures.

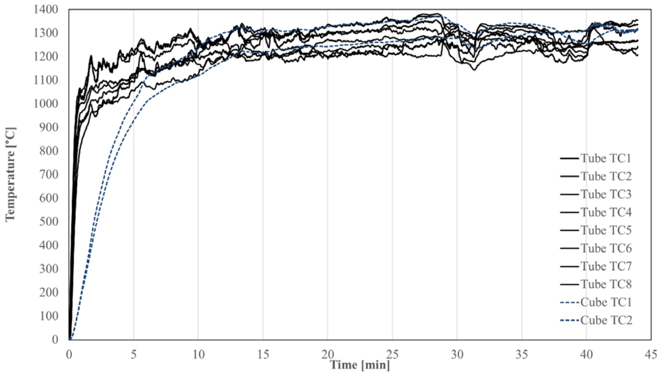

Figure D: Flame temperatures measured using tube and cube thermocouples (TC) in one high temperature jet fire test. Solid lines indicate measurement by tube thermocouples, dashed lines indicate use of cube thermocouples.

For the proposed unified heat flux measurement method presented in this paper, the tube thermocouple is considered as the most convenient and reliable for measuring flame temperatures.

Comparing the tube to the cube thermocouple, the tube heats up faster to stabilize at high temperatures. The relative slow heating of the cube thermocouple could be useful for some purposes, when studying the transient heating of a cold object with a certain heat capacity during the first few minutes in a fire. The derivative of the temperature over time and the heat capacity of the steel cube can be used to calculate the net heat absorbed by the cube. Another difference between the tube and the cube is that the cube has a larger surface area and should be more dominated by the radiation temperature than the smaller tube thermocouple. The smaller tube thermocouple should be more dominated by the gas temperature in the flame. The main purpose of using cube thermocouples has therefore been merely to verify that the temperature level measured by the tube thermocouples also is dominated by the radiation in the furnace.

Comparing the tube thermocouple to the plate thermocouple, the benefit of the plate thermocouples is that they are directional, while the tube is omnidirectional. However, as previously mentioned, standard plate thermocouples are not sufficiently robust, while tube thermocouples are sufficiently robust to survive a high temperature jet fire test. The optimal thermocouple system for high temperature jet fires might therefore be a cross between the two: a more robust, but at the same time directional thermocouple.

Choice of calculation method: The measured flame temperatures can be used to estimate the heat flux. By flame temperatures we mean temperatures measured inside a small object engulfed in the flames. This object will receive and emit heat to and from its surroundings by convection and radiation. The measured temperature will be a mix of the gas temperature around the surfaces of the object and the radiation temperature that the object exchanges with the surroundings. This temperature can also be called adiabatic surface temperature or equilibrium temperature. [4]

The suggested method for heat flux calculation is to follow the Stefan-Boltzmann relation of temperature and heat flux, see eq (1).

$$\dot{q}'' = \sigma\, \varepsilon\, T_{flame}^4 \qquad (1)$$

Where $\dot{q}''$ is the heat flux (kW/m^2), σ is the Stefan Boltzmann constant ($5.67 \cdot 10^{-11}$ kW/m^{2}K^4), ε is the emissivity of the thermocouple surface (between 0-1) and T_{flame} is the flame temperature (K).

For a black body radiation ($\varepsilon = 1$) this gives 350 kW/m^2 for 1303 °C and 250 kW/m^2 for 1176 °C. Lower emissivity could be chosen, which would require higher temperatures to obtain the same flux levels. For practical purposes in a jet fire, however, steel surfaces located within the re-circulation chamber are oxidized quickly, giving an assumed emissivity near 1.

If an average heat flux level for the entire duration of a test is needed, this should be calculated starting from t = 5 minutes until test end. The heat flux given in eq. (1) assumes that the difference between gas and surface temperature is negligible, that is, convection is not considered. The assumption is most valid after the initial heating period of the specimen and re-circulation chamber. This assumption gives a more conservative test, in terms of the temperature exposure to the test specimen.

Choice of re-circulation chamber design: To reach temperatures up to 1303 °C, which by the calculation in eq (1) corresponds to the 350 kW/m^2 heat flux level, adjustment of the standard re-circulation chamber design is proposed. Flame temperature measurements from 20 standard jet fire tests according to ISO 22899-1 (picture in Figure A) and from 55 jet fire tests using the modified test setup (picture in Figure B) have been collected during the period 2012-2016. Figure E presents the statistical distribution of all the temperature measurements for the two different test setup configurations. All the measured temperatures are grouped in 5 °C intervals and the relative frequency of each of the intervals is calculated. For clarity, the figures E and F are plotted as continuous distribution instead of discrete histograms.

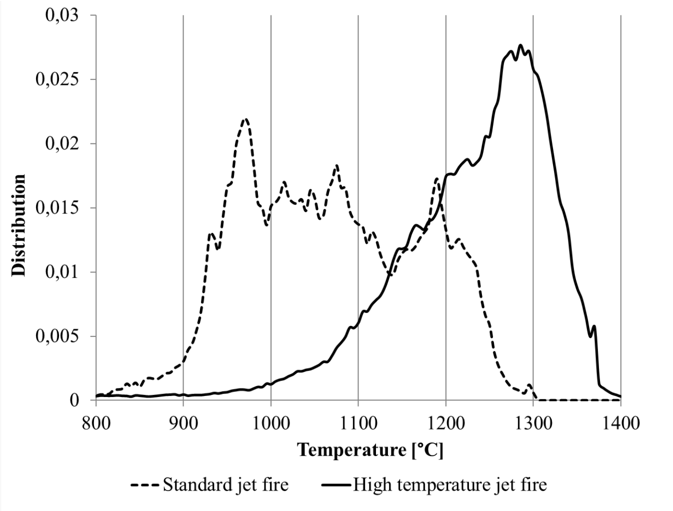

Figure E: Flame temperature measurement distribution in jet fire tests. Data from a total of 20 standard jet fire tests, with average temperature 1061 ± 115°C, median 1059 °C (dashed line). Data from a total of 55 high temperature jet fire tests, with average temperature 1218 ± 179 °C, median 1244 °C (solid line). All temperature measuremets at each recorded time step are included in the data set.

The majority of the measured flame temperatures in the standard test setup are spread over a wider temperature range than the flame temperatures in the modified setup. It is also clear that higher temperatures are reached using the modified test setup and that this method is superior for heat exposures around 1300 °C.

These results emphasize that even with the same fuel leak rate, differences in compartmentation of the fire plume have a large impact on the temperature levels.

Choice of representative flame temperature: NORSOK S001 [1] defines fire loads in two categories, local peak heat load (250 kW/m^2 and 350 kW/m^2) and global average heat load (100 kW/m^2). In the method presented here, the local peak heat load has been interpreted as the local maximum flame temperature for each time step. In practice, the highest measured temperature from the group of thermocouples placed in the re-circulation chamber is selected, for each time step. This is the suggested temperature (T_{flame}) to be used in the heat flux calculation in eq (1). An alternative to the selected approach is to use the average flame temperature during a test.

The difference between the two approaches is given in Figure F. As can be seen, the proposed interpretation of using local maximum flame temperatures will give a less conservative approach than using the average flame temperature. The flame temperatures would need to be even higher during a test in order to reach 350 kW/m^2 heat flux level using average values. However, with local maximum temperatures of around 1300 °C (see Figure E), the calculated heat flux levels are assumed to meet the requirements for risk analysis purposes, as will be discussed below.

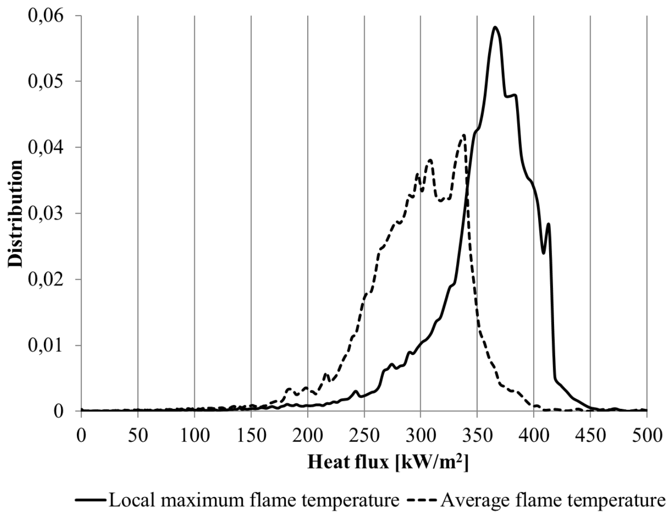

Figure F: Distribution of calculated heat flux using local maximum (solid line) and using average flame temperatures (dashed line). Data is collected from 55 high temperature jet fire tests, each with about 6 thermocouples.

Relevance for real-scale fire incidents: The calculation method presented in this paper is an approximation for a complex reality, but it is still considered to give a representative measurement for the temperature that an object would reach when placed inside a relatively large jet fire.

It could be argued that the high temperatures reached in the modified re-circulation chamber are unrealistically high for real-scale incidents. However, these jet fire temperatures are similar to those measured in other large-scale fire experiments [5]. Flame temperatures above 1370 °C have been measured in large scale tests with oil pool fires on the sea surface [6-8], for various fuels in tunnel fires tests [5,9] and for large crude oil spray and pool fires [10-11]. Common for all these is that the scale is larger than what is normally found at laboratory fire experiments, but still significantly smaller than the fires observed in severe incidents, such as on the Piper Alpha and on the Deepwater Horizon.

We argue that temperature measurements in a defined measurement object give a good representation of the thermal exposure to an object engulfed in a flame. If a specific heat flux level is required, as is the case in NORSOK S001 [1], the calculation method presented in this paper will give a conservative, but relevant calculation from these measured temperatures to heat flux levels.

Summary and conclusions:

A jet fire test method to reach and measure 350 kW/m^2 heat flux exposure has been described. A modified version of the standard ISO 22899-1 jet fire test setup is used to enable high temperature jet fire testing. The fuel type, nozzle dimension and fuel flow rate are kept unchanged. The geometry of the re-circulation chamber has been modified, to increase compartmentation of the jet flame.

The thermocouple type found to be most suited for temperature measurement of the flame is 8 mm diameter steel tubes with 1.5 mm encapsulated thermocouple inside. A suggested point of development is to make a directional, robust thermocouple.

The Stefan-Boltzmann relation between temperature and heat flux is used for calculating heat flux levels, assuming negligible convection contribution.

The method presented here has been found to be simple, robust, repeatable and practically applicable, in a large series of jet fire tests. We propose that the presented test setup, measurement method and calculation method should be used for documentation of the performance of passive fire protection products in high temperature jet fires.

Acknowledgements:

The data material presented in this paper is collected partially during confidential testing for clients. However, no information which could identify clients, products or individual test results has been presented here.

References

[1] NORSOK S001, Technical safety, Norwegian Technology Standards Institution, Oslo, 2008

[2] ISO 22899-1, Determination of the resistance to jet fires of passive fire protection materials. Part 1: General requirements, ISO Copyright office, Switzerland, 2007

[3] NS-EN 1363-1: 2012, Fire resistance tests – Part 1: General Requirements. Standards Norway, Oslo

[4] U. Wickström, Temperature calculation in fire safety engineering. Switzerland: Springer, 2016

[5] R. Wighus, A. Brandt, and C. Sesseng, “Radiation from Large Flames,” presented at the 8th International Seminar on Fire and Explosion Hazards. Hefei, China, April 2016.

[6] R. Wighus and L. E. Lønvik, “NBL A07132 Fire on the sea surface: Experiments at Svalbard 1994. Summary report of the Winter and Summer Experiments.,” http://nbl.sintef.no/publication/lists/docs/NBL_A07132.pdf, SINTEF Report NBL A07132, 2007.

[7] R. Wighus, G. Drangsholt, K. Nygård, G. Tronstad, and J. P. Stensaas, “NBL A07130 Fire on the sea surface: Technical report for the Svalbard winter experiment in April-May 1994,” SINTEF Report NBL A07130, 2007.

[8] R. Wighus, L. E. Lønvik, and K. Nygård, “NBL A07131 Fire on the sea surface: Technical report for the Svalbard summer experiment in September - October 1994,” SINTEF Report NBL A07131, 2007.

[9] “Summary of the Large Scale Fire Tests in the Runehamar Tunnel in Norway, conducted in association with the UPTUN Research Program.,” edited by J. Brekelmans and R. van den Bosch, TNO, Nederland, 2003, available at: http://www.vegvesen.no/_attachment/61890/binary/15101

[10] G. A. Chamberlain, M. A. Persaud, R. Wighus, and G. Drangsholt, “NBL A08102 Blast and Fire Engineering for Topside Structures. Test Programme F3, Confined Jet and Pool Fires. Final report.,” SINTEF Report NBL A08102, 2008.

[11] G. A. Chamberlain, “An experimental study of large-scale compartment fires,” Process Safety and Environmental Protection: Tranactions of the Institution of Chemical Engineers, no. Part B, pp. 72:211-219, 1994