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Fire safety engineering — Requirements governing algebraic formulae —

Part 7: Radiation heat flux received from an open pool fire

Ingénierie de la sécurité incendie — Exigences régissant les formules algébriques —

Partie 7: Flux de chaleur rayonné reçu d'un feu en nappe ouvert

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

A list of all parts in the ISO 24678 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This corrected version of ISO 24678-7:2019 incorporates the following corrections:

Figure 1: "ISO 23932" has been corrected to "ISO 23932-1:2018". The box titled "selection of engineering methods" has been highlighted.

Figure A.2: The symbol *m&*, estimation of mass burning rate, has been corrected to $\dot{m}''$.

B.3.1.2, Formula B.2: first parenthesis, under the squared root, "x+1/x−1" has been corrected to read "x−1/x+1".

B.3.1.2, Formula B.5: second denominator "r" has been corrected to "r^2".

B.3.3.2.1, Figure B.11 a): The black triangles have been removed.

B.3.3.3.1, Figure B.12: The black rectangle has been removed.

B.3.3.3.1, Figure B.13: "1" has been removed from inside the figure.

B.3.3.3.1, Figure B.14: The horizontal line has been removed.

Introduction

This document is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. It is expected that the users of this document are appropriately qualified and competent in the field of fire safety engineering. It is particularly important that the users understand the parameters within which particular methodologies can be used.

Algebraic formulae conforming to the requirements of this document are used with other engineering calculation methods during fire safety design. Such a design is preceded by the establishment of a context, including the fire safety goals and objectives to be met, as well as performance criteria when a trial fire safety design is subject to specified design fire scenarios. Engineering calculation methods are used to determine if these performance criteria are met by a particular design and if not, how the design needs to be modified.

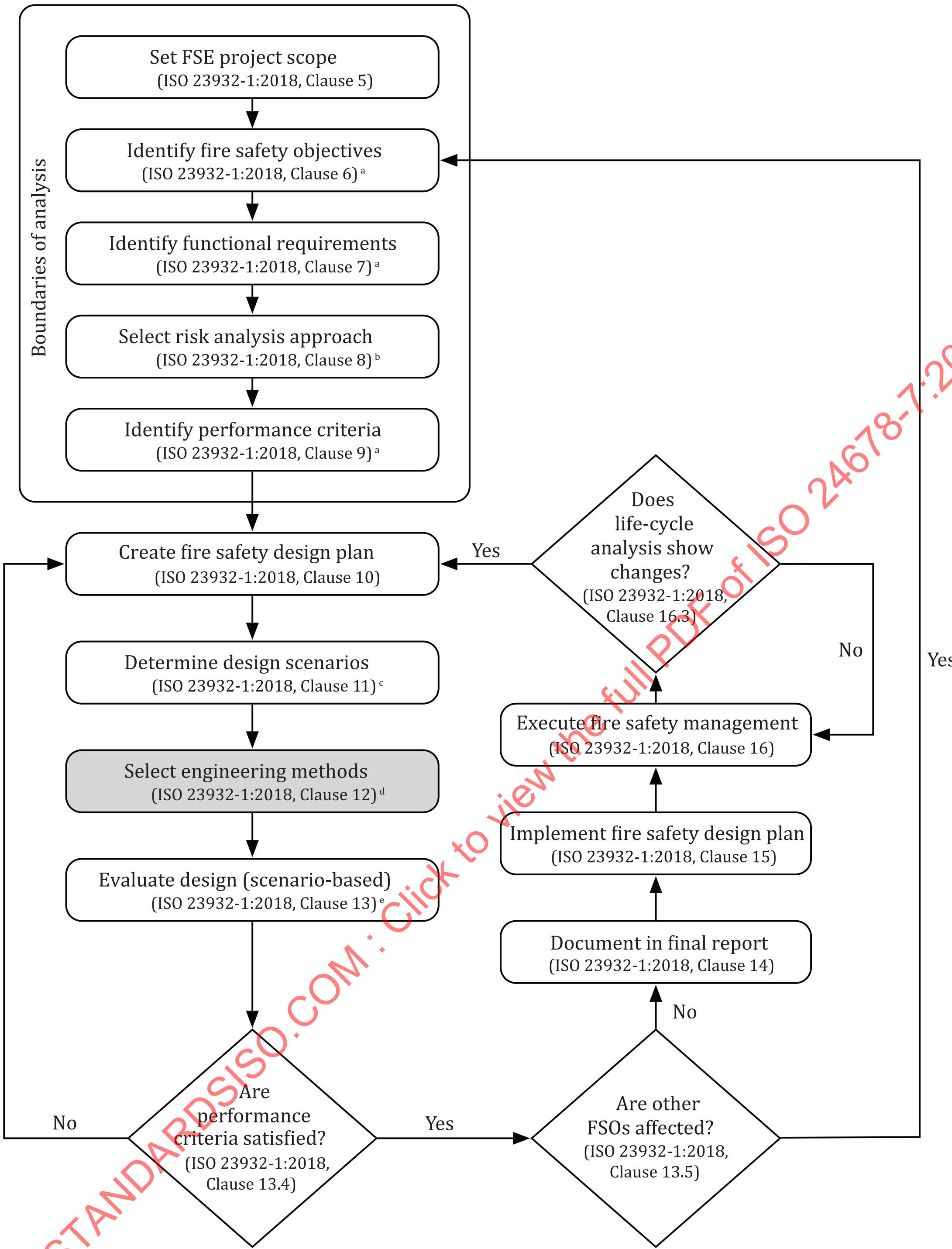
The subjects of engineering calculations include the fire safety design of entirely new built environments, such as buildings, ships or vehicles as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document can be useful for estimating the consequences of design fire scenarios. Such formulae are valuable for allowing the practitioner to quickly determine how a proposed fire safety design needs to be modified to meet performance criteria and to compare among multiple trial designs. Detailed numerical calculations can be carried out until the final design documentation. Examples of areas where algebraic formulae have been applicable include determination of convective and radiative heat transfer from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings, and analysis of compartment fire hazards such as smoke filling and flashover. However, the simple models often have stringent limitations and are less likely to include the effects of multiple phenomena occurring in the design fire scenarios.

The general principles are described in ISO 23932-1, which provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property and the environment. ISO 23932-1 provides the process (i.e. necessary steps) and essential elements to conduct a robust performance-based fire safety design.

ISO 23932-1 is supported by a set of available fire safety engineering International Standards on the methods and data needed for all the steps in a fire safety engineering design as summarized in Figure 1 (taken from ISO 23932-1:2018, Clause 4). The set includes ISO 16730-1, ISO 16733-1, ISO 16732, ISO 16734, ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-6, ISO/TS 24679, ISO 23932-1, ISO/TS 29761 and other supporting technical reports that provide examples of and guidance on the application of these standards.

Each International Standard supporting the global fire safety engineering analysis and information system includes language in the introduction to tie the standard to the steps in the fire safety engineering design process outlined in ISO 23932-1. ISO 23932-1 requires that engineering methods be selected properly to predict the fire consequences of specific scenarios and scenario elements (ISO 23932-1:2018, Clause 10). Pursuant to the requirements of ISO 23932-1, this document provides the requirements governing algebraic formulae for fire safety engineering. This step in the fire safety engineering process is shown as a highlighted box in Figure 1 and described in ISO 23932-1.



Key

a See also ISO/TR 16576 (Examples).

b See also ISO 16732-1, ISO 16733-1, ISO/TS 29761.

c See also ISO 16732-1, ISO 16733-1, ISO/TS 29761.

d See also ISO/TS 13447, ISO 16730-1, ISO/TR 16730-2 to 5 (Examples), ISO 16734, ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-6.

[e] See also ISO/TR 16738, ISO 16733-1.

NOTE Documents linked to large parts of the FSE process: ISO 16732-1, ISO 16733-1, ISO/TS 24679, ISO/TS 29761, ISO/TR 16732-2 to 3 (Examples), ISO/TR 24679-2 to 4 and 6 (Examples).

Figure 1 — Flow chart illustrating the fire safety engineering design process (from ISO 23932-1:2018)

Fire safety engineering — Requirements governing algebraic formulae —

Part 7: Radiation heat flux received from an open pool fire

1 Scope

The requirements in this document govern the application of a set of explicit algebraic formulae for the calculation of specific characteristics of radiation heat flux from an open pool fire.

This document is an implementation of the general requirements provided in ISO 16730-1 for the case of fire dynamics calculations involving a set of explicit algebraic formulae.

This document is arranged in the form of a template, where specific information relevant to the algebraic formulae is provided to satisfy the following types of general requirements:

a) description of physical phenomena addressed by the calculation method;

b) documentation of the calculation procedure and its scientific basis;

c) limitations of the calculation method;

d) input parameters for the calculation method; and

e) domain of applicability of the calculation method.

Examples of sets of algebraic formulae meeting the requirements of this document are provided in Annexes A and B. Annex A contains a set of algebraic formulae for radiation heat fluxes from a circular or near-circular open pool fire. Annex B contains formulae for configuration factors of a flame to a target.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5725 (all parts), *Precision of test methods — Determination of repeatability and reproducibility for a standard test method by inter-laboratory tests*

ISO 13943, *Fire safety — Vocabulary*

ISO 16730-1, *Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General*

ISO 16733-1, *Fire safety engineering — Selection of design fire scenarios and design fires — Part 1: Selection of design fire scenarios*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
pool fire
burning of a horizontal, upward-facing, combustible fuel of liquids, liquefied gases or horizontally placed melting plastic materials

3.2
open pool fire
pool fire (3.1) in open air or in a space that is very large relative to the size of the fire, where the confined effect of the built environment on the behaviour of its flame is negligible

Note 1 to entry: The open pool fire characteristics are dependent on the outside conditions such as wind.

3.3
circular or near circular pool fire
pool fire (3.1) whose geometry can be approximated by a circular shape

Note 1 to entry: In case of an elongated pool, this approximation is valid if the ratio between the longest dimension and the shortest dimension is not greater than 2 to 3[1].

3.4
equivalent diameter
diameter of a circular pool whose plan area is equivalent with rectangular or irregularly shaped pools

3.5
absorption coefficient
the fraction of absorbed radiation intensity per unit length of radiation path.

3.6
radiative fraction
ratio of the radiative heat release rate to the total heat release rate

3.7
mean flame height
time-averaged height of flames above the base of a fire, defined as the elevation where the probability of finding flames is 50 %

3.8
atmospheric transmissivity
ratio of the transmitted radiation intensity after passing through unit length of a participating medium (carbon dioxide, water vapour, dust and fog) to the radiation intensity that would have passed the same distance through clean air

4 Requirements governing the description of physical phenomena

4.1 Radiation heat flux from an open pool fire is a complex thermo-physical and chemical phenomenon that can be highly transient or nearly steady-state. Radiation heat flux depends on the combustible properties, the combustible's geometry and the environment between the radiation source and the "target" that receives the heat flux. The properties of the target need to be considered when further calculations of target behaviour are assessed, e.g. injuries to people, malfunction/damage of a piece of equipment, ignition of a combustible material, deteriorations of structural members. The physical phenomena described in this document are concerned with only the calculations of the radiation heat flux received by a target from an open pool fire.

4.2 General types of pool sources, pool geometry and relative positions of the considered targets (including the position of radiation screens placed between the pool and the targets) shall be described with the aid of diagrams.

4.3 Scenario elements, as determined by ISO 16733-1, to which specific formulae apply shall be clearly identified. Radiation heat flux characteristics to be calculated and their useful ranges shall be clearly identified, including those characteristics inferred by association with calculated quantities, if applicable.

4.4 Physical phenomena (e.g. pool formation during a continuous release, interaction between fire and extinguishing materials) to which specific formulae apply shall be clearly identified.

4.5 Because different formulae describe different pool source radiative flame characteristics (see 4.2) or apply to different scenarios (see 4.3), it shall be shown that if there is more than one method to calculate a given quantity, guidance shall be given on the selection of appropriate methods. An example describing the choice of a method is given in Annex A.

5 Requirements governing the documentation

5.1 The general requirements governing the documentation can be found in ISO 16730-1.

5.2 The process to be followed in performing calculations shall be described through a set of algebraic formulae.

5.3 Each formula shall be presented in a separate clause containing a statement that describes the output of the formula, as well as explanatory notes and limitations unique to the presented formula.

5.4 Each variable in the formula set shall be clearly defined, along with appropriate SI units. Formula versions with dimensionless coefficients are usually preferred.

5.5 The scientific basis for the formula set shall be provided through references to recognized handbooks, peer-reviewed scientific literature or through derivations, where appropriate.

5.6 Examples shall be provided to demonstrate how the formula set is evaluated using values for all input parameters consistent with all the requirements of Clause 5.

6 Requirements governing the limitations

6.1 Quantitative limits on the direct application of the algebraic formula set to calculate output parameters, consistent with the scenarios described in Clause 4, shall be provided.

6.2 Cautions on the use of the algebraic formula set within a more general calculation method shall be provided including checks of consistency with the other relations used in the calculation method and the numerical process employed.

7 Requirements governing the input parameters

7.1 Input parameters for the set of algebraic formulae shall be identified clearly, e.g. mass burning rate, pool diameter, etc.

7.2 Sources of data for input parameters shall be identified or provided explicitly.

7.3 The valid ranges for input parameters shall be listed as specified in ISO 16730-1.

8 Requirements governing the domain of applicability

8.1 One or more collections of measurement data shall be identified to establish the domain of applicability of the set of algebraic formulae. The data shall have a certain level of quality in accordance with ISO 5725(all parts) (e.g. repeatability and reproducibility). The level of quality shall be assessed through a documented standardised procedure.

8.2 The domain of applicability of the algebraic formulae shall be determined through comparison with the measurement data as given in 8.1.

8.3 Potential sources of errors that limit the set of algebraic formulae to the specific scenarios shall be identified, e.g. the assumption of quiescent atmosphere.

Annex A
(informative)

Algebraic formulae for thermal radiation from a circular or near circular open pool fire

A.1 Symbols and abbreviated terms used in this Annex

A_s	plan area of a pool fire source (m^2)
D	equivalent diameter of a pool fire source (m)
E	emissive power of a flame (kW/m^2)
E_{max}	emissive power of the luminous region of a flame (kW/m^2)
E_s	emissive power of smoke (kW/m^2)
F_{12}	configuration factor of a flame to a target (–)
$F_{12,h}$	configuration factor of a flame to a horizontal target (–)
$F_{12,v}$	configuration factor of a flame to a vertical target (–)
g	gravity acceleration (9,81 m/s^2)
H	vertical distance from flame base to a target (m)
k	radiation absorption coefficient of a flame from various fuels (m^{-1})
L	mean flame height (m)
$\dot{m}''$	mass burning rate per unit area (kg/m^2·s)
$\dot{m}''_{\infty}$	mass burning rate per unit area of a sufficiently large pool (kg/m^2·s)
m^*	non-dimensional burning rate (–)
$\dot{q}''$	radiation heat flux to a target (kW/m^2)
$\dot{Q}$	heat release rate (kW)
u_w	wind velocity (m/s)
u^*	non-dimensional wind velocity
X	horizontal distance to a target from the centre of a flame (m)
β	radiation absorption coefficient of a flame taking the diameter as the characteristic length (m^{-1})
χ_r	radiative fraction (–)
ΔH_c	heat of combustion of fuel (J/kg)

θ flame tilt angle (rad)

ρ_a density of normal ambient air (1,2 kg/m^3)

τ atmospheric transmissivity (–)

A.2 Description of the physical phenomena addressed by the algebraic formula set

A.2.1 General

The formulae described in this annex provide radiation heat fluxes from a pool fire to a target and can be applicable to various locations and orientations. The set of formulae is particularly convenient for horizontal and vertical target orientations. The formulae presented here have been validated on sooty liquid hydrocarbon fires.

A.2.2 General description of the calculation method

Estimating the radiation heat flux received by a target from a pool fire involves the three following steps:

— determination of the characteristics of the pool fire (burning surface, mass burning rate, duration of the fire, time to steady-state conditions, etc.);

— determination of the thermal radiation characteristics of the pool fire (flame height, flame tilt, emissive power of the flames, etc.);

— calculation of the radiation heat flux received by a target (configuration factor of a flame to a target, atmospheric transmissivity along radiation path).

It is very important that a single method be used for all the three steps of this process. The methods presented in this annex constitute whole methods and its parts cannot be changed. The validation of the whole model needs to be considered, not its components individually.

A.2.3 Scenario elements to which the set of formulae is applicable

The set of formulae is applicable to thermal radiation from quasi-steady-state pool fire flames that are approximately circular or square in plan area in an unobstructed environment, unless otherwise stated.

A.2.4 Self-consistency of the set of formulae

The set of formulae provided in this annex has been derived and reviewed to ensure that the calculation results from different formulae in the set are consistent (i.e. do not produce conflicts).

A.2.5 Standards and other documents where the set of formulae is used

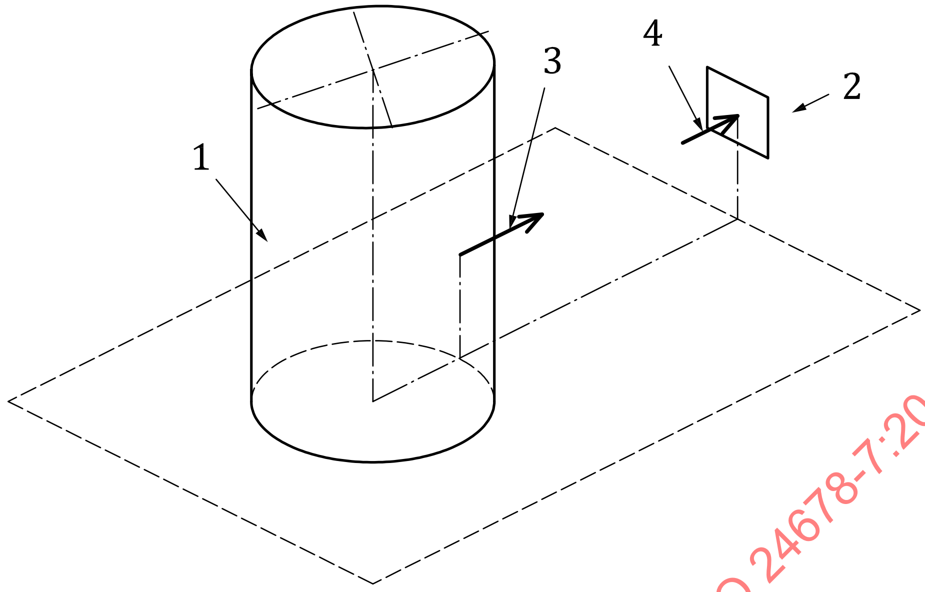
None specified.

A.3 Documentation of the set of formulae

A.3.1 General

As shown in Figure A.1, radiation is emitted by a flame and received by a target. The heat flux received by a target from a pool fire can be calculated with the following algebraic formula:

$$\dot{q}'' = \tau E F_{12} \tag{A.1}$$



Key

1 flame (surface 1)

2 target (surface 2)

3 emissions (to all directions)

4 heat flux to a target

Figure A.1 — Radiation from a flame to a target

Figure A.2 depicts the successive steps to estimate the radiation heat flux received by a target from a pool fire. From the specified burning object characteristics, the heat release rate and the diameter of the pool, when not given, are estimated. The emissive power from the flame surface is assumed to be a function of the diameter of the pool. The flame geometry is calculated by using the heat release rate and fire source diameter. Finally, the configuration factor of a flame to a target is calculated. The effect of blockage by a participation medium such as soot, water vapour and dipole gases is considered, where necessary, as atmospheric transmissivity.

The target is considered as an infinitesimally small plane element, which is assumed to be located at the minimum distance between the fire and the real target. Because configuration factors are also considered in the calculations of the physical phenomena, the point is associated with an element surface. In the rest of this document, the target will be seen as a unit surface of a target. In this annex, a solid cylindrical flame model is adopted. As presented in Figure A.2, the method is composed of different interdependent sub-models, mean flame height, emissive power and so on.

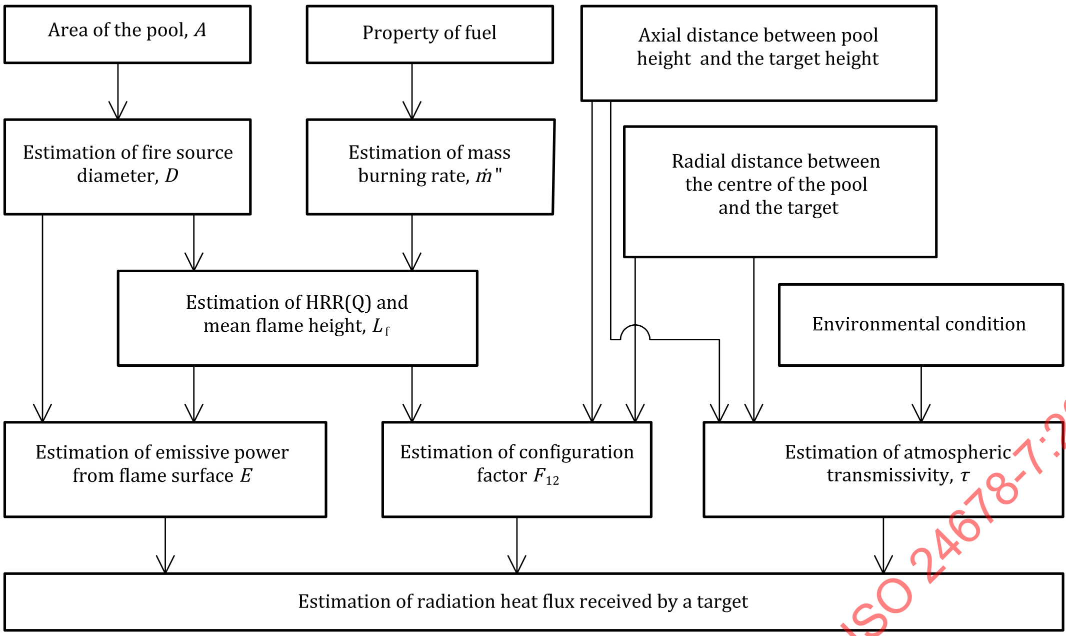


Figure A.2 — Calculation process of radiation heat flux received by a target from a pool fire

A.3.2 Geometry and heat release rate of pool fires

A.3.2.1 Equivalent diameter of a pool fire source

The equivalent diameter of a pool fire source, D, is given by Formula (A.2):

$$D = \sqrt{\frac{4A_s}{\pi}} \qquad \text{(A.2)}$$

A.3.2.2 Heat release rate

The heat release rate, $\dot{Q}$, is given by:

$$\dot{Q} = \Delta H_c \dot{m}'' A_s \qquad \text{(A.3)}$$

Examples of mass burning rate and net heat of combustion are shown in Table A.1. Using these values, the mass burning rate is estimated by[2]:

$$\dot{m}'' = \dot{m}''_{\infty}(1 - e^{-kD}) \qquad \text{(A.4)}$$

NOTE Formula (A.4) is valid for large pool fires with $D > 0{,}2$ m.

Table A.1 — Net heat of combustion and mass burning rate of various fuels[3]

Fuel	Net heat of combustion ΔH_c (MJ/kg)	Mass burning rate at sufficiently large pool $\dot{m}''_{\infty}$ (kg/m^2·s)	Radiation absorption coefficient k (m^{-1})
Liquid H_2	120	0,017	6,1
LNG	50,0	0,078	1,1
LP-gas	46,0	0,099	1,4

Table A.1 *(continued)*

Fuel	Net heat of combustion ΔH_c (MJ/kg)	Mass burning rate at sufficiently large pool $\dot{m}''_\infty$ (kg/m²·s)	Radiation absorption coefficient k (m⁻¹)
Methanol	20,0	0,017	—
Ethanol	26,8	0,015	—
Butane	42,7	0,078	2,7
Hexane	44,7	0,074	1,9
Heptane	44,6	0,101	1,1
benzene	40,1	0,085	2,7
Xylene	40,8	0,090	1,4
Acetone	25,8	0,041	1,9
Dioxane	26,2	0,018	5,4
Diethyl ether	34,2	0,085	0,7
Benzine	44,7	0,048	3,6
Gasoline	43,7	0,055	2,1
Kerosine	43,2	0,039	3,5
JP-4	43,5	0,051	3,6
JP-5	43,0	0,054	1,6
Transformer oil	46,4	0,039	0,7
Fuel oil, heavy	39,7	0,035	1,7
Crude oil	42,5	0,022	2,8

A.3.3 Cylindrical solid flame model and surface emissive power

A.3.3.1 Selection of methods

Several models have been developed based on the solid flame concept. The most common one is the cylindrical solid flame model as shown in Figure A.1. This model has been chosen to represent the radiative emitter by the lateral envelope of the flame as well as the upper disk.

There are various methods for estimating the surface emissive power. The surface emissive power is related to the area of the cylindrical solid flame and the flame height. The Mudan-Croce method[4], Shokri-Beyler method[5] and the radiative fraction method are adopted in this annex. Each set of formulae corresponds to a specific fuel type and a range of fuel diameter. The Mudan-Croce method is accompanied with the Thomas' formula for flame height[6][7] and flame tilt. The Shokri-Beyler method is associated with the Heskestad's formula for flame height[8] as described in ISO 16734. As the estimation formula for the emissive power is related to the surface area of flame, mixing various methods need to be avoided.

A.3.3.2 Mudan-Croce's method

A.3.3.2.1 General

The Mudan-Croce method, for estimating the incident heat flux from a pool fire, suggests the following formulae for the effective emissive power of gasoline, kerosene, and JP-4 flames, but it is not recommended for LNG. The set of formulae uses correlations of flame height developed by Thomas from wood crib experiments. In case of windy conditions, the flame tilt angle is calculated by correlation developed by Thomas. This method is recommended in the range of diameter of approximately 1 m to 60 m.

A.3.3.2.2 Flame height by Thomas' formula

In case of quiescent atmosphere, the flame height is calculated by [6]:

$$\frac{L}{D}=42\left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{0,61} \quad (A.5)$$

NOTE Formula (A.5) is suitable for large open pool fires. See A.4.1 for details.

In the presence of wind, the flame length and tilt angle are[6]:

$$\frac{L}{D}=55\left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{0,67}(u^*)^{-0,21} \quad (A.6)$$

$$\cos\theta=\begin{cases}1 & (u^*\le 1)\\ 1/\sqrt{u^*} & (u^*>1)\end{cases} \quad (A.7)$$

where the non-dimensional wind velocity is:

$$u^*=\frac{u_w}{(g\dot{m}''D/\rho_a)^{1/3}} \quad (A.8)$$

A.3.3.2.3 Emissive power by Mudan-Croce's formula

The average and uniform emissive power at the flame surface of a pool fire, E, is given by the experimental correlation (Formula A.9)[4], with E_{max} = 140 kW/m^2, E_s = 20 kW/m^2 and β = 0,12 m^{-1}. The average and uniform emissive power at the flame surface depends only on the pool diameter.

$$E=E_{max}e^{-\beta D}+E_s(1-e^{-\beta D}) \quad (A.9)$$

The formula takes into consideration the screening effects of soot. Limitations of the uniform average emissive power may arise when the target is close to the flame region at the rim of a pool fire where the emissive power might be underestimated.

A.3.3.3 Shokri-Beyler's method

A.3.3.3.1 General

The flame is assumed to be a cylindrical, homogeneous radiator with an average emissive power. Shokri's formula for emissive power is derived in association with the flame height by Heskestad's formula. This method is mostly applicable at heat fluxes greater than 5 kW/m^2. The pool diameter ranges from 1 m to 50 m and is mainly concerned with LNG and JP-5.

A.3.3.3.2 Flame height by Heskestad's formula

Heskestad's formula[8] is applied to calculate the flame height as specified in ISO 16734.

$$L=-1,02D+0,235\dot{Q}^{2/5} \quad (A.10)$$

A.3.3.3.3 Emissive power by Shokri's formula

The effective emissive power of the pool fire is given by Shokri[5] as:

$$E=58\,(10^{-0,008\,23D}) \quad (A.11)$$

A.3.3.4 Radiative fraction method

A.3.3.4.1 General

For relatively small pool diameters, the calculation formula is available for various fuels. The formula is a purely geometrical representation of the redistribution of the radiant energy on a cylindrical envelope.

A.3.3.4.2 Flame height by Heskestad's formula

The flame height is calculated by Heskestad's formula as shown in (Formula A.10).

A.3.3.4.3 Emissive power by radiative fraction

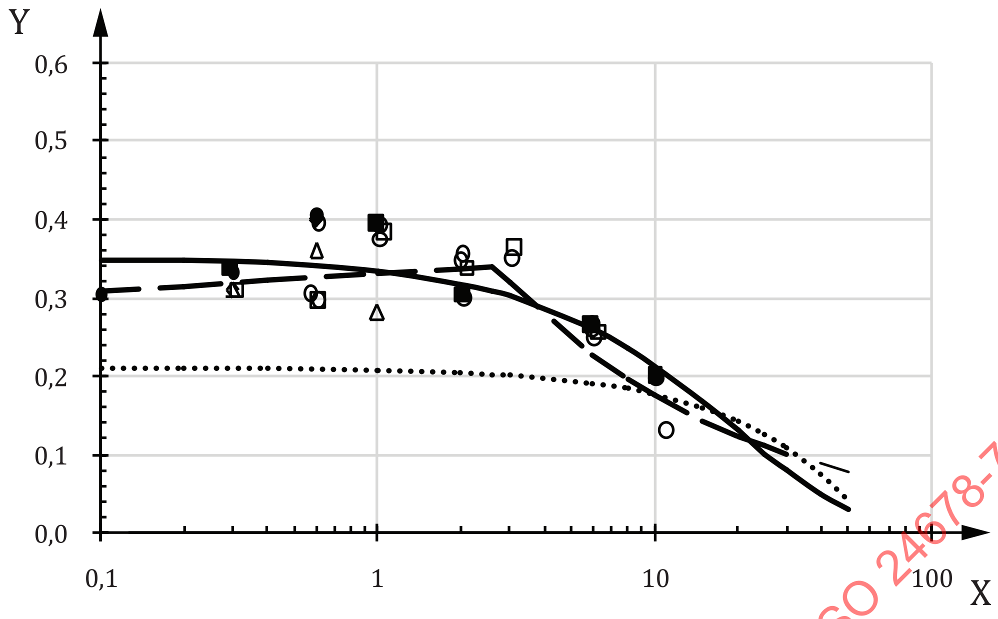
The emissive power E is calculated considering a uniform distribution of the radiative fraction of the heat release on the side and top surfaces of a cylinder,

$$E = \frac{\chi_r \dot{Q}}{\pi D L + \dfrac{\pi D^2}{4}} \qquad \text{(A.12)}$$

where the radiative fraction of the energy released is correlated with the pool diameter as shown in Table A.2[9] to [11]. Examples of radiative fraction of various fuels and liquid materials are shown in Figures A.3 to A.6[12] to [21]. When the formulae do not provide conservative estimates of radiative fraction, it is recommended to choose an appropriate value depending on the fuel type and pool diameter.

Table A.2 — Examples of calculation formulae for radiative fraction of energy release

Fuel	Formula	Ref.
kerosene, fuel oil, gasoline, JP-4,LNG, Methanol, Heptane, Toluene, Crude oil	$\chi_r = 0{,}21 - 0{,}003\,4D \quad (D < 50\ \text{m})$	SFPE guide[9]
heptane, crude oil, kerosene	$\chi_r = 0{,}35\exp(-0{,}05D) \quad (2 \le D \le 50)$	McGrattan et al.[10]
heptane	$\chi_r = \begin{cases} 0{,}33D^{0{,}03} & (0{,}2 < D \le 2{,}6) \\ 0{,}55D^{-0{,}5} & (2{,}6 < D) \end{cases}$	Yang et al.[11]
kerosene	$\chi_r = \begin{cases} 0{,}32D^{0{,}08} & (0{,}2 < D < 2) \\ 0{,}48D^{-0{,}6} & (2 < D) \end{cases}$	



Key

X pool diamater (m)

Y radiative fraction (−)

□ Koseki & Yumoto (1988)

○ Koseki (1989)

■ Koseki & Hayasaka (1989)

◇ Hamnis et al. (1991)

◆ Klassen & Hamnis (1991)

△ Klassen & Gore (1994)

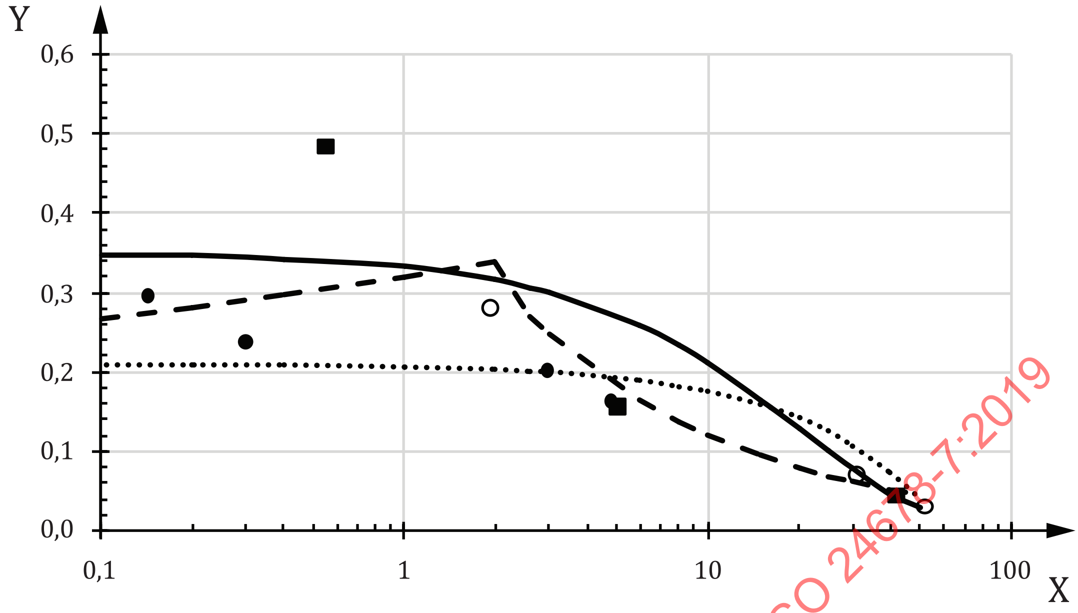
● Buch et al. (1997)

—— McGrattan et al. (2000)

.... SFPE guide (1999)

— - Yang et al. (1994)

Figure A.3 — Measured radiative fraction of heptane pool fires[12] to [18] and formulae[9] to [11] in Table A.2



Key

X pool diamater (m)

Y radiative fraction (–)

● Souil et al. (1986)

○ Koseki & Yumoto (1988)

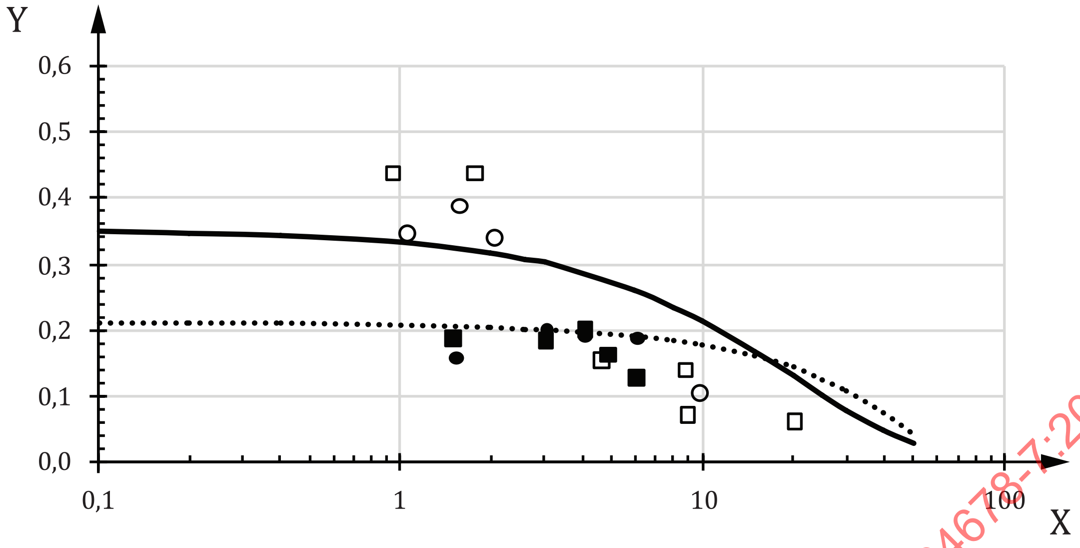
■ Koseki (1989)

—— McGrattan et al. (2000)

.... SFPE guide (1999)

– – Yang et al. (1994)

Figure A.4 — Measured radiative fraction of kerosene pool fires[13][14][19] and formulae[9] to [11] in Table A.2



Key

X pool diamater (m)

Y radiative fraction (–)

○ JP4, Koseki (1989)

● diesel oil, Munos (2007)

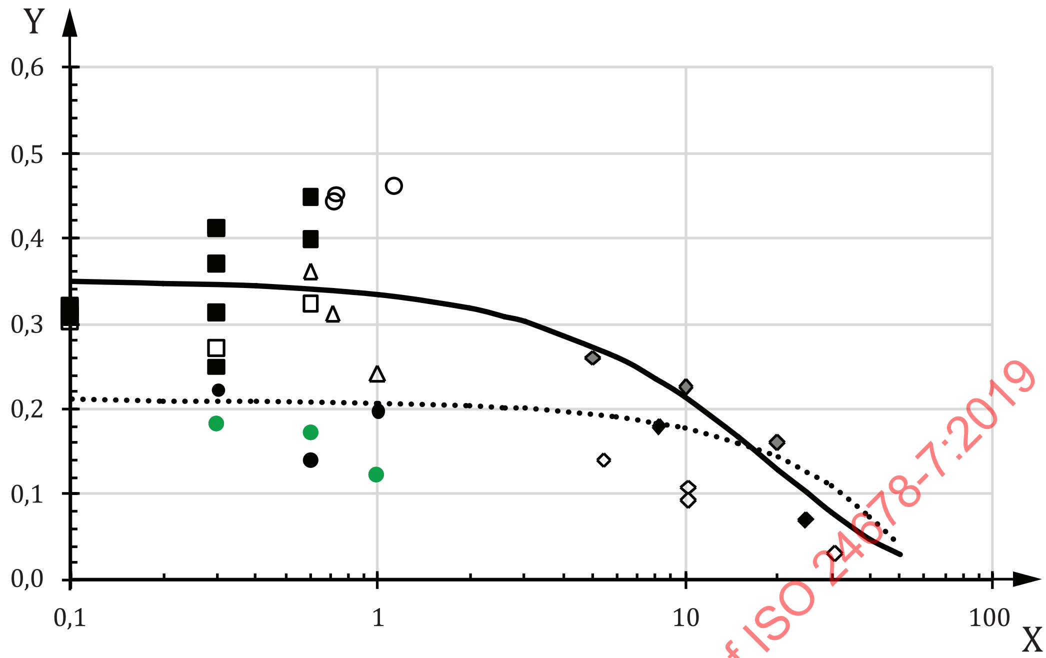
□ gasoline, Koseki (1989)

■ gasoline, Munos (2007)

—— McGrattan et al. (2000)

……. SFPE guide (1999)

Figure A.5 — Measured radiative fraction of pool fires of various fuels[13][20] and formulae[9] to [11] in Table A.2



Key

X pool diamater (m)
Y radiative fraction (−)
○ benzene, Koseki (1989)
● methanol, Buch (1997)
● methanol, Klassen & Gore (1994)
□ acetone, Buch (1997)
△ toluene, Klassen & Gore (1994)
■ silicone oil, Buch (1997)
◇ crude oil, Koseki & Yumoto (1988)
◆ crude oil, Koseki (1989)
◆ crude oil, Koseki et al. (2000)
—— McGrattan et al. (2000)
.... SFPE guide (1999)

Figure A.6 — Measured radiative fraction of pool fires of various fuels[12][13][17][18][21] and formulae[9][10] in Table A.2

A.3.4 Configuration factors

The configuration factors are calculated by flame length, flame width, distance to target, flame tilt and orientation of the target. The explicit forms of calculation formulae are summarized in Annex B.

A.3.5 Atmospheric transmissivity

In most cases, the atmospheric transmissivity is approximated as unity. When it is desirable to consider the absorption by the atmosphere between a flame and a target, the effect of the absorbing medium can be applied. The principal constituents that absorb thermal radiation are soot (C), water vapour (H_2O) and carbon dioxide (CO_2)[22].

A.4 Scientific basis for the set of formulae

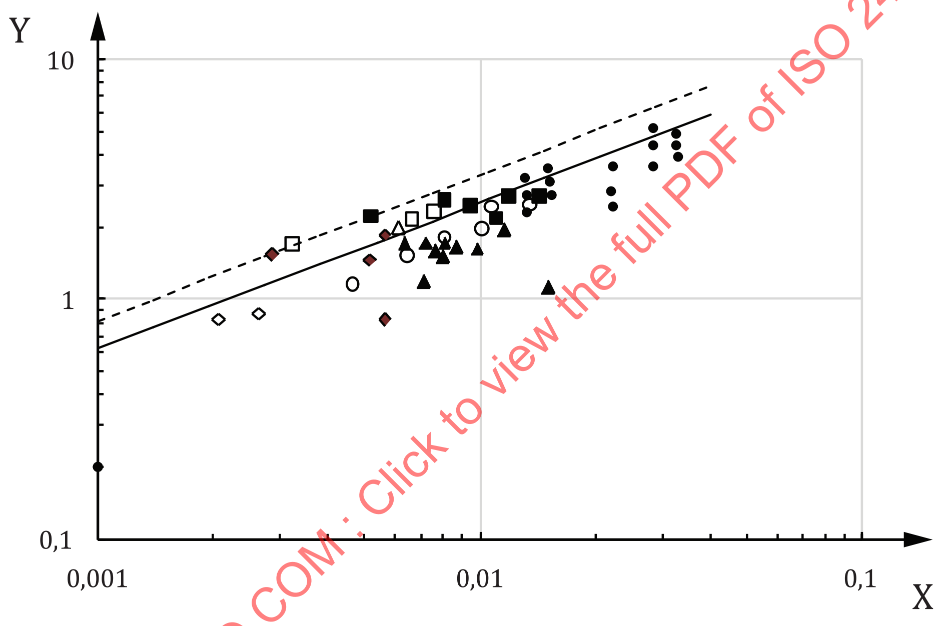
A.4.1 Flame height

The formulae for flame height were developed by Thomas for wood crib fires and by Heskestad for common fuels. The formulae are developed by a scaling law of fire plume, and compared with experimental observations. Heskestad's plume is described in ISO 16734:2006, Annex A.

Many investigators have developed correlations for turbulent flame heights in a quiescent air environment. Most are based on the dimensional analysis of experimental data using Froude modelling principles. Some are based on approximate theoretical models involving some empirical factors. These correlations are generally cast in terms of a non-dimensional burning rate as follows.

$$m^* = \frac{\dot{m}''}{\rho_a \sqrt{gD}} \tag{A.13}$$

The ratio of flame height to pool diameter is plotted versus non-dimensional burning rate in Figure A.7.



Key

X pool diameter (m)

Y flame height/pool diameter ratio (−)

—— no wind, Formula (A.5)

---- with wind, Formula (A.6)

● LNG pool fires on water

■ LNG pool fires on land

▲ LNG pool fires on land

○ gasoline fires on land

◇ kerosene fires on land

◆ gasoline, kerosene, diesel oil

□ LNG, kerosene

△ acetone

Figure A.7 — Comparison of Thomas' formulae with experimental data gathered by Mudan[23]

A.4.2 Configuration factor

The formulae for configuration factors have been developed to describe radiation heat transfer for general purposes not only for fire calculations. The factor is calculated only by geometrical relationships between a flame and a target. See Annex B for detailed information.

A.5 Formula-set limitations

A.5.1 Shape of fire source

The set of formulae described in this annex assumes circular or near circular pool fires. Rectangular or irregularly-shaped pool sources with aspect ratios greater than 2 to 3[1] require other models than the ones described in this annex, as the equivalent diameter cannot be calculated by Formula (A.1).

A.5.2 Property of fuel

This annex deals with sooty hydrocarbon fires only. Fire sources affected by extinguishing agents are not considered in this annex.

A.5.3 Emissive power

The emissive power depends largely on the pool diameter and slightly depends on the fuel type. The use of correct values is essential for accurate calculations. It should be noted that experimental data are fitted with the cylindrical flame model to determine surface emissivity. Thus the emissive power is a model dependent parameter.

A.5.4 Proximity to boundaries

The flame height is different when the pool is close to a vertical boundary. Rectangular pools, with a wall at one or more sides and three-dimensional fire sources having restricted air access, cannot be considered in this annex. In addition, if a fire plume is close to the enclosure boundary, reflection and re-radiation by the wall surface need to be considered.

A.6 Formula-set input parameters

A.6.1 Heat release rate

The parameter, $\dot{Q}$, is the rate of heat that is actually released by a fire under specific environmental conditions, as measured by a calorimeter that is based on product gas collection to determine O_2, CO_2 and CO generation rates, or as otherwise specified. This parameter is normally obtained from a design fire scenario. Further information on fire calorimetry is described in ISO 24473.

A.6.2 Radiative fraction

The radiative fraction of a flame, χ_R, is typically in the range of 0,3 to 0,4 for liquid fuels burning in a relatively small pool but can be down to 0,2 or smaller as the fire source diameter increases.

A.6.3 Fire source diameter

The fire source diameter is normally obtained from a design fire scenario. For rectangular fire sources, an equivalent diameter, D, is obtained from Formula (A.2), which uses a circular source having the same area as the fire source.

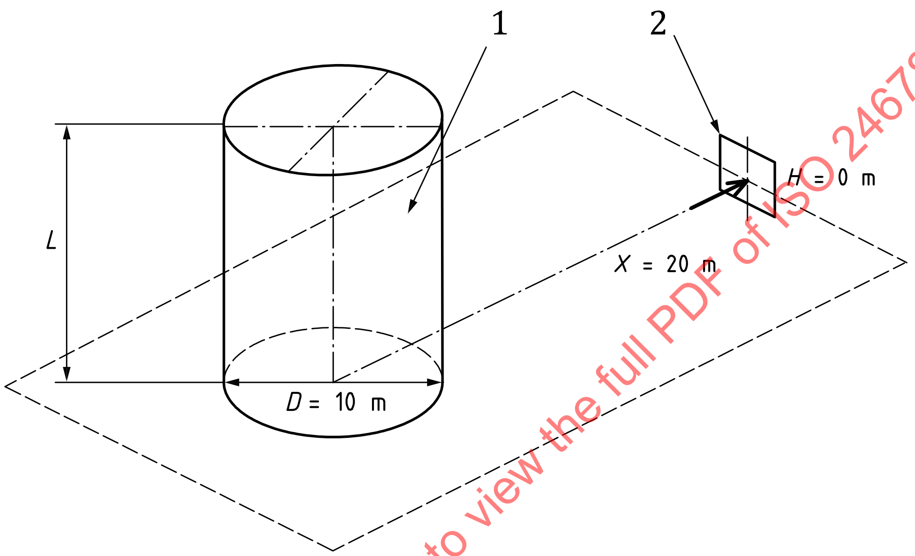
A.7 Domain of applicability of the set of formulae

The domain of applicability of the set of formulae in this annex can be determined from the scientific literature references given in A.3 and A.4. Configuration factors can be applied to any flame size and distance of the target to the flame.

A.8 Calculation examples

A.8.1 Calculation conditions

Calculate the radiation heat flux to a vertical target on the ground level at a distance of 20 m from a circular kerosene pool fire of 10-m diameter as shown in Figure A.8.



Key

1 flame (surface 1)

2 target (surface 2)

Figure A.8 — Calculation example of the radiation heat flux to a vertical target

A.8.2 Burning and heat release rates

Using Formula (A.4), the mass burning rate per unit area is:

$$\dot{m}'' = \dot{m}''_{\infty}(1-e^{-kD}) = 0{,}039 \times \{1-\exp(-3{,}5\times 10)\} = 0{,}039\ 0\ \ (\text{kg/m}^2\cdot\text{s}) \quad \text{(A.14)}$$

Using Formula (A.3), the heat release rate is:

$$\dot{Q} = \Delta H_c \dot{m}'' A_s = 43{,}2 \times 0{,}039\ 0 \times \frac{3{,}14\times 10^2}{4} = 132{,}3\ \ (\text{MW}) \quad \text{(A.15)}$$

A.8.3 Mudan-Croce's method

The flame height is calculated by Formula (A.5) as:

$$L = 42\left(\frac{\dot{m}''}{\rho_a \sqrt{gD}}\right)^{0,61} D = 42 \times \left(\frac{0,039}{1,205 \times \sqrt{9,81 \times 10,0}}\right)^{0,61} \times 10,0 = 12,8 \ \ (\text{m}) \tag{A.16}$$

The emissive power is calculate by Formula (A.9) as:

$$E = E_{max} e^{-\beta D} + E_s (1 - e^{-\beta D}) = 140 \exp(-0,12 \times 10) + 20\{1 - \exp(-0,12 \times 10)\} = 56,1 \ \ (\text{kW/m}^2) \tag{A.17}$$

The configuration factor for this arrangement is calculated by Formula (B.2) in Annex B as:

$$F_{12\text{v}} = f_{\text{cyl-v}}\left(\frac{L}{D/2}, \frac{X}{D/2}\right) = f_{\text{cyl-v}}\left(\frac{12,8}{10,0/2}, \frac{20,0}{10,0/2}\right) = 0,092\ 9 \ \ (-) \tag{A.18}$$

The heat flux received by the target is calculated by Formula (A.1) as:

$$q = \tau E F_{12\text{v}} = 1,0 \times 56,1 \times 0,092\ 9 = 5,22 \ \ (\text{kW/m}^2) \tag{A.19}$$

A.8.4 Shokri–Beyler's method

The flame height is calculated by Heskestad's Formula (A.10) as:

$$L = -1,02D + 0,235\dot{Q}^{2/5} = -1,02 \times 10 + 0,235 \times 132\ 300^{2/5} = 16,1 \ \ (\text{m}) \tag{A.20}$$

The emissive power from the flame surface is calculated by Formula (A.11) as:

$$E = 58(10^{-0,008\ 23D}) = 58 \times 10^{-0,008\ 23 \times 10} = 48,0 \ \ (\text{kW/m}^2) \tag{A.21}$$

The configuration factor for this arrangement is calculated by Formula (B.2) in Annex B as:

$$F_{12\text{v}} = f_{\text{cyl-v}}\left(\frac{L}{D/2}, \frac{X}{D/2}\right) = f_{\text{cyl-v}}\left(\frac{16,1}{10,0/2}, \frac{20,0}{10,0/2}\right) = 0,103 \ \ (-) \tag{A.22}$$

The heat flux received by the target is calculated by Formula (A.1) as:

$$q = \tau E F_{12\text{v}} = 1,0 \times 48,0 \times 0,103 = 4,94 \ \ (\text{kW/m}^2) \tag{A.23}$$

A.8.5 Radiative fraction method

The radiative fraction is calculated by the second formula in Table A.2 as:

$$\chi_r = 0,35 \exp(-0,05D) = 0,35 \times \exp(-0,05 \times 10) = 0,212 \tag{A.24}$$

The emissive power is calculated by Formula (A.12) using the Heskestad's flame height, Formula (A.20), as:

$$E = \frac{\chi_r \dot{Q}''}{\frac{\pi}{4} D^2 + \pi D L} = \frac{0,212 \times 132\ 300}{\frac{3,14}{4} \times 10^2 + 3,14 \times 10 \times 16,1} = 48,1 \ \ (\text{kW/m}^2) \tag{A.25}$$

The heat flux received by the target is calculated by Formula (A.1) as:

$$q = F_{12\text{v}} E = 0,103 \times 48,1 = 4,96 \ \ (\text{kW/m}^2) \tag{A.26}$$

Annex B
(informative)

Configuration factors of a cylindrical flame to a target

B.1 Symbols and abbreviated terms used in this Annex

$f_{\text{cyl-h}}$ configuration factor of side surface of an upright cylinder to a horizontal target(–)

$f_{\text{cyl}(\theta)\text{-h}}$ configuration factor of side surface of a tilted cylinder to a horizontal target(–)

$f_{\text{cyl-v}}$ configuration factor of side surface of an upright cylinder to a vertical target(–)

$f_{\text{cyl}(\theta)\text{-v}}$ configuration factor of side surface of a tilted cylinder to a vertical target(–)

$f_{\text{cir-h}}$ configuration factor of a horizontal circular disk to a horizontal target(–)

$f_{\text{cir-v}}$ configuration factor of a horizontal circular disk to a vertical target(–)

$f_{\text{rect-h}}$ configuration factor of a vertical rectangular surface to a horizontal target (–)

$f_{\text{rect-v}}$ configuration factor of a vertical rectangular surface to a vertical target (–)

F configuration factor of a flame to a target at arbitrary orientation

F_{v} configuration factor of a flame to a vertical target (–)

F_{h} configuration factor of a flame to a horizontal target (–)

h non-dimensional vertical distance from flame base to target, H/R (–)

H vertical distance from flame base to a target (m)

l non-dimensional flame height, L/R (–)

l_e effective non-dimensional flame height (–)

L flame height (m)

L_{e} effective flame height (m)

r_{pq} distance from point p on emitting surface to point q on target (m)

R radius of a flame (m)

R_{e} effective radius of a flame (m)

x non-dimensional horizontal distance from flame axis to a target, X/R (–)

x_e effective non-dimensional horizontal distance from flame axis to a target, X/R_e (–)

X horizontal distance from flame axis to a target (m)

θ flame tilt angle toward downstream (rad.)

θ_p angle between outward normal vector at point p and a vector connecting point p to point q (rad.)

θ_q angle between outward normal vector at point q and a vector connecting point q to point p (rad.)

B.2 Description of physical phenomena addressed by the set of formulae

B.2.1 General

The formulae provide configuration factors of a cylindrical flame to a target. The flame may be either upright or tilted by the effect of wind. The target may be horizontal, vertical or inclined facing the flame.

B.2.2 General description of the calculation method

The formulae have been derived by integrating the definition of the configuration factor. The formulae depend only on the geometrical arrangement of the emitting surface and the target, namely, the flame height, radius of flame, flame tilt, location and orientation of the target.

B.2.3 Scenario elements to which the set of formulae is applicable

The set of formulae is applicable to calculate the configuration factors from a flame to a target.

B.2.4 Self-consistency of the set of formulae

The set of formulae provided in this annex has been derived and reviewed to ensure that calculation results from different formulae in the set are consistent (i.e. they do not produce conflicts).

B.2.5 Standards and other documents where the set of formulae is used

None specified.

B.3 Formula-set documentation

B.3.1 Configuration factor of an upright flame to a target

B.3.1.1 Geometry to be considered

The flame geometry is approximated by a cylinder of radius R and of height L. Depending on the height of the target relative to the flame, calculation procedures are classified into the following four sub-clauses.

B.3.1.2 Target on the same height as the flame base

As shown in Figures B.1 and B.2, the target is located at a distance X from the flame axis. The height of the target is the same as the flame base. The configuration factor to the target is calculated by:

a) Vertical target facing the flame[24]

$$F_v = f_{cyl\text{-}v}(l, x) \tag{B.1}$$

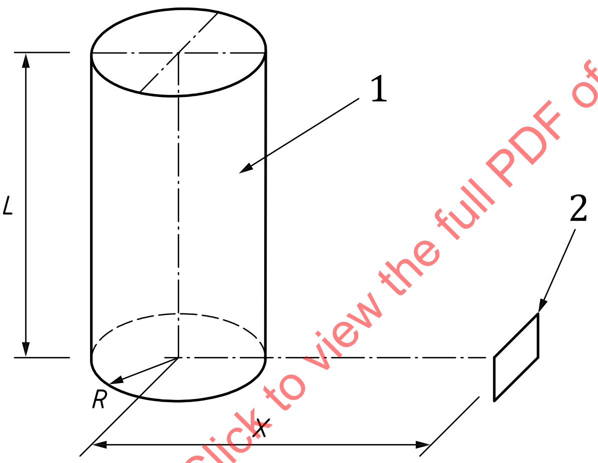
$$f_{\text{cyl-v}}(l,x) \equiv \frac{1}{\pi}\left[-\frac{l}{x}\tan^{-1}\left(\sqrt{\frac{x-1}{x+1}}\right)+\frac{1}{x}\tan^{-1}\left(\frac{l}{\sqrt{x^2-1}}\right) + \frac{l}{x}\frac{l^2+x^2+1}{\sqrt{l^2+(x+1)^2}\sqrt{l^2+(x-1)^2}}\tan^{-1}\left(\sqrt{\frac{x-1}{x+1}}\sqrt{\frac{l^2+(x+1)^2}{l^2+(x-1)^2}}\right)\right] \quad \text{(B.2)}$$

b) Horizontal target facing upward[24]

$$F_h = f_{\text{cyl-h}}(l,x) \quad \text{(B.3)}$$

$$f_{\text{cyl-h}}(l,x) \equiv \frac{1}{\pi}\left[\tan^{-1}\sqrt{\frac{x+1}{x-1}} - \frac{l^2+x^2-1}{\sqrt{l^2+(x+1)^2}\sqrt{l^2+(x-1)^2}}\tan^{-1}\left(\sqrt{\frac{x-1}{x+1}}\sqrt{\frac{l^2+(x+1)^2}{l^2+(x-1)^2}}\right)\right] \quad \text{(B.4)}$$

NOTE In the case of a horizontal surface facing downward, the total system can be transposed upside down to apply Formula (B.4).

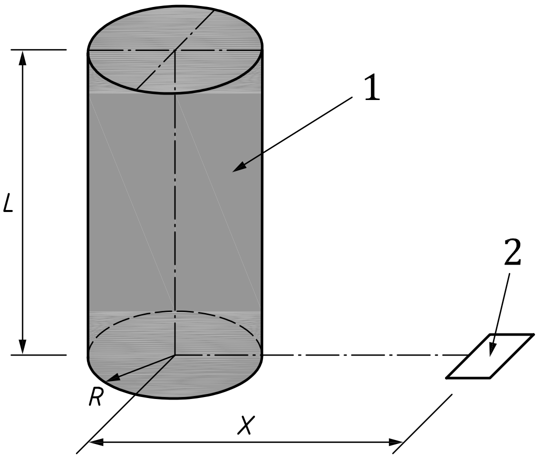


Key

1 flame

2 target on vertical surface

Figure B.1 — Geometry of flame and target in vertical surface facing the flame

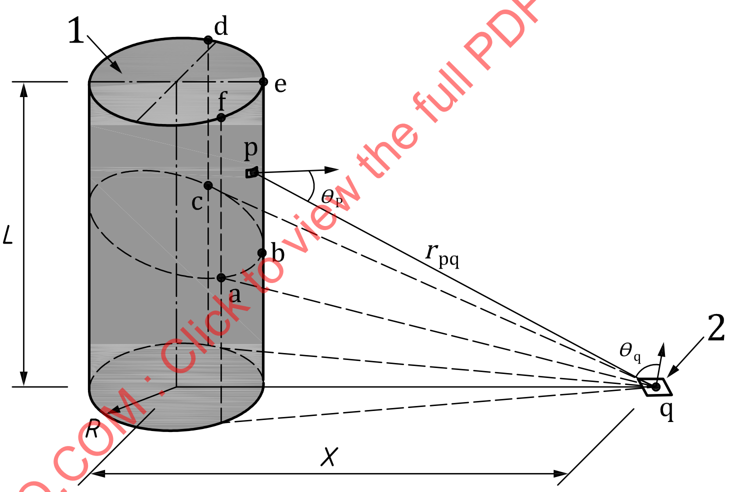


Key

1 flame

2 target on horizontal surface facing upward

Figure B.2 — Geometry of flame and target in horizontal upward surface



Key

1 flame

2 target

a-b-c-d-e-f-a perimeter of area visible from target

Figure B.3 — Geometry of flame and target in arbitrary orientation

c) Arbitrary orientations

For other orientations, explicit formulae are given only for special cases[25][26][27][28]. In general cases, numerical integration can be applied based on the definition of the configuration factor as shown in Figure B.3,

$$F = \frac{1}{\pi} \iint \frac{\cos\theta_{\mathrm{p}} \cos\theta_{\mathrm{q}}}{r^2_{\mathrm{pq}}} dA = \frac{1}{\pi} \sum_j \frac{\cos\theta_{\mathrm{p,j}} \cos\theta_{\mathrm{q,j}}}{r^2_{\mathrm{pq,j}}} dA_j \quad \text{(B.5)}$$

where the integral in Formula (B.5) corresponds to the area integral with respect to the visible part of the side surface of the cylinder. In the case of Figure B.3, the area surrounded by points a-b-c-d-e-f-a is considered.

d) Calculation examples

Let the radius of a flame be R = 1 m, the flame height be L = 6 m, the configuration factors to vertical and horizontal surfaces located at X = 4 m from the flame axis are calculated as follows:

The non–dimensional flame height:

$$l = L / R = 6 / 1 = 6{,}0 \tag{B.6}$$

The non-dimensional horizontal distance:

$$x = X / R = 4 / 1 = 4{,}0 \tag{B.7}$$

The configuration factor of the flame to the vertical target:

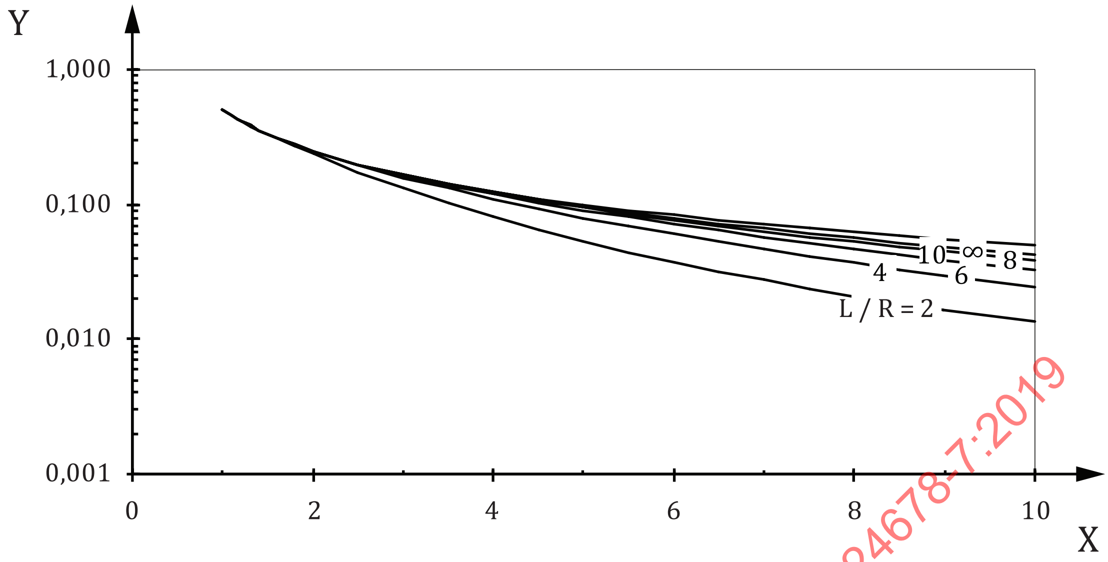
$$\begin{aligned} F_\text{v} &= f_\text{cyl-v}(6{,}0;4{,}0) \\ &= \frac{1}{3{,}14}\left[-\frac{6{,}0}{4{,}0}\tan^{-1}\sqrt{\frac{4{,}0-1}{4{,}0+1}} + \frac{1}{4{,}0}\tan^{-1}\frac{6{,}0}{\sqrt{4{,}0^2-1}} \right. \\ &\left. + \frac{6{,}0}{4{,}0}\frac{6{,}0^2+4{,}0^2+1}{\sqrt{6{,}0^2+(4{,}0+1)^2}\sqrt{6{,}0^2+(4{,}0-1)^2}}\tan^{-1}\left(\sqrt{\frac{4{,}0-1}{4{,}0+1}}\sqrt{\frac{6{,}0^2+(4{,}0+1)^2}{6{,}0^2+(4{,}0-1)^2}}\right)\right] \\ &= \frac{1}{3{,}14}(-0{,}989+0{,}243+1{,}114) \\ &= 0{,}119 \end{aligned} \tag{B.8}$$

The configuration factor to the horizontal target:

$$\begin{aligned} F_\text{h} &= f_\text{cyl-h}(6{,}0;4{,}0) \\ &= \frac{1}{3{,}14}\left[\tan^{-1}\sqrt{\frac{4{,}0+1}{4{,}0-1}} \right. \\ &\left. - \frac{6{,}0^2+4{,}0^2-1}{\sqrt{6{,}0^2+(4{,}0+1)^2}\sqrt{6{,}0^2+(4{,}0-1)^2}}\tan^{-1}\left(\sqrt{\frac{4{,}0-1}{4{,}0+1}}\sqrt{\frac{6{,}0^2+(4{,}0+1)^2}{6{,}0^2+(4{,}0-1)^2}}\right)\right] \\ &= \frac{1}{3{,}14}(0{,}912-0{,}714) \\ &= 0{,}062\,8 \end{aligned} \tag{B.9}$$

e) Design diagram

The configuration factors for practical ranges are plotted in Figures B.4 for the vertical target and in Figure B.5 for the horizontal target. The non-dimensional flame height, l (=L/R) is in the range of 2 to infinity. The non-dimensional horizontal distance, x (=X/R), is in the range of 1 to 10.

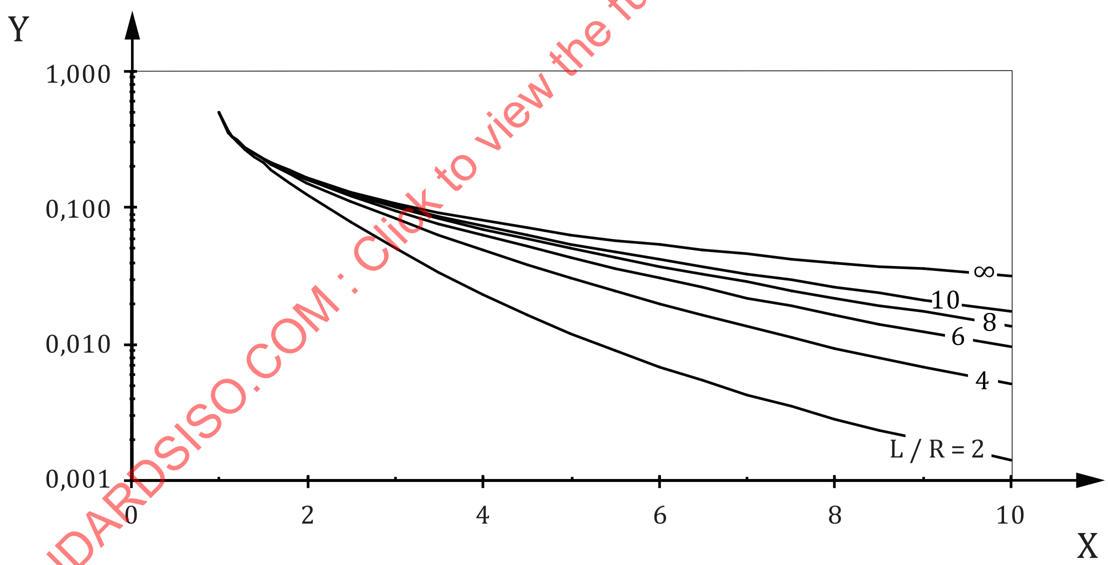


Key

X non-dimensional horizontal distance, X/R (−)

Y configuration factor of a flame to a vertical target, $f_{cyl\text{-}v}$ (−)

Figure B.4 — Configuration factors of a cylindrical flame to a vertical target facing the flame



Key

X non-dimensional horizontal distance, X/R (−)

Y configuration factor of a flame to a horizontal target, $f_{cyl\text{-}h}$ (−)

Figure B.5 — Configuration factors of a cylindrical flame to a horizontal target facing upward

B.3.1.3 Target below the flame base

To calculate the configuration factors to targets below the flame base, Formula (B.2) or Formula (B.4) is superimposed. The cylinder is extended downward to the same height as the target. The configuration factors are calculated for the total part including the extended part. Then the same formula is applied only to the extended part. The configuration factors from the side surface of the cylinder to the target are calculated by the difference of two calculated values as indicated by Formula (B.10) or (B.12). If the bottom surface is visible from the target, the configuration factor of the bottom disk to the target is calculated by Formula (B.11) or (B.13) and added as the third term of Formula (B.10) or (B.12).

a) Vertical target facing the flame

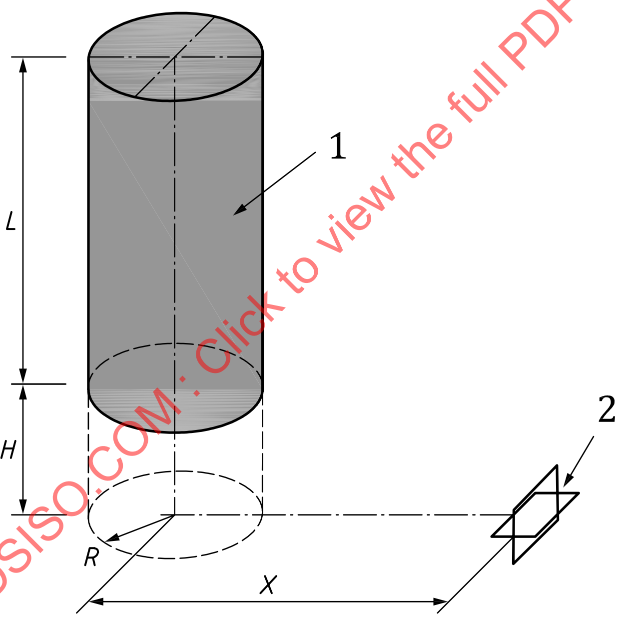
$$F_{\text{v}} = f_{\text{cyl-v}}\left(\frac{L+H}{R},\frac{X}{R}\right) - f_{\text{cyl-v}}\left(\frac{H}{R},\frac{X}{R}\right) + f_{\text{cir-v}}\left(\frac{H}{X},\frac{X}{R}\right) \tag{B.10}$$

$$f_{\text{cir-v}}(h,x) = \frac{1}{2}\frac{h}{x}\left(\frac{h^2+x^2+1}{\sqrt{(h^2+x^2+1)^2-4x^2}}-1\right) \tag{B.11}$$

b) Horizontal target facing upward

$$F_{\text{h}} = f_{\text{cyl-h}}\left(\frac{L+H}{R},\frac{X}{R}\right) - f_{\text{cyl-h}}\left(\frac{H}{R},\frac{X}{R}\right) + f_{\text{cir-h}}\left(\frac{H}{R},\frac{X}{R}\right) \tag{B.12}$$

$$f_{\text{cir-h}}(h,x) \equiv \frac{1}{2}\left(1-\frac{h^2+x^2-1}{\sqrt{(h^2+x^2+1)^2-4x^2}}\right) \tag{B.13}$$



Key

1 flame

2 target on vertical or horizontal surface

Figure B.6 — Calculation of a configuration factor to a vertical or horizontal target below the flame base

B.3.1.4 Target between the flame base and top

If the target is located between the bottom and top of flame, the upper and lower parts of the flame are considered separately.

a) Vertical target facing the flame

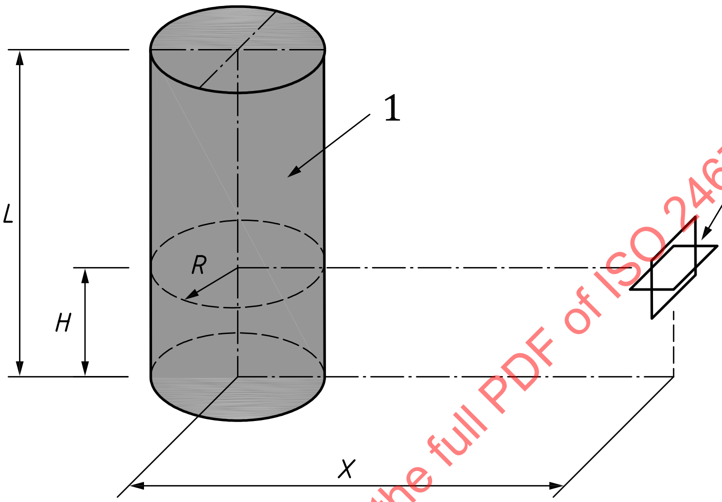
Formula (B.2) is applied to the upper and lower parts of the flame separately.

$$F_v = f_{\text{cyl-v}}\left(\frac{L-H}{R}, \frac{X}{R}\right) + f_{\text{cyl-v}}\left(\frac{H}{R}, \frac{X}{R}\right) \quad \text{(B.14)}$$

b) Horizontal target facing upward

Formula (B.2) is applied only to the upper part of the flame. The lower part of the flame is invisible from the target.

$$F_h = f_{\text{cyl-h}}\left(\frac{L-H}{R}, \frac{X}{R}\right) \quad \text{(B.15)}$$



Key

1 flame

2 target on vertical or horizontal surface

Figure B.7 — Calculation of a configuration factor to a vertical or horizontal target between the flame base and top

B.3.1.5 Target above the flame top

Similar to the case of a target below the flame base, the cylinder is extended upward to the same height as the target.

a) Vertical target facing the flame

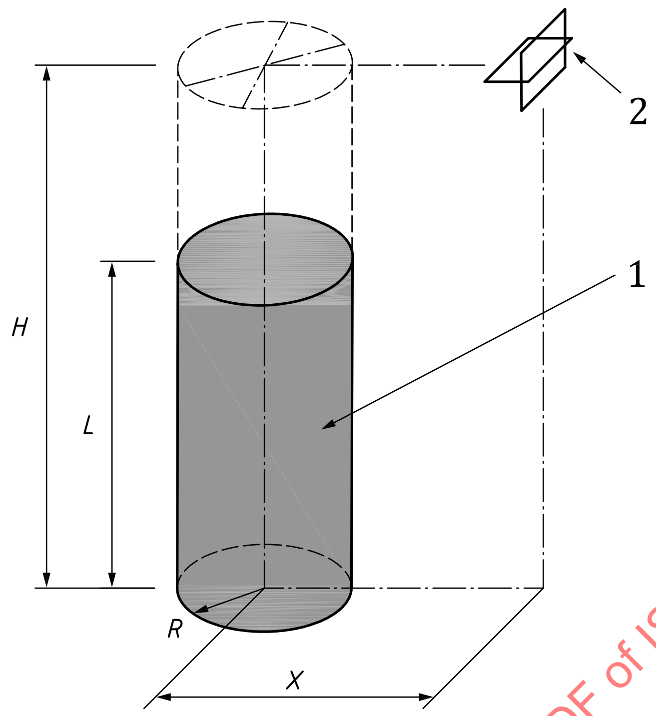
The configuration factors are calculated for the total part including the extended part by using Formula (B.2) or (B.4) and for the extended part. Then the two values are subtracted. If the top surface is visible from the target, the configuration factor of the top disk to the target is calculated by Formula (B.11) or (B.13) and added as the third term of Formula (B.16).

$$F_v = f_{\text{cyl-v}}\left(\frac{H}{R}, \frac{X}{R}\right) - f_{\text{cyl-v}}\left(\frac{H-L}{R}, \frac{X}{R}\right) + f_{\text{cir-v}}\left(\frac{H-L}{R}, \frac{X}{R}\right) \quad \text{(B.16)}$$

b) Horizontal target facing upward

Since the flame is invisible from the target, the configuration factor is zero.

$$F_h = 0 \quad \text{(B.17)}$$



Key

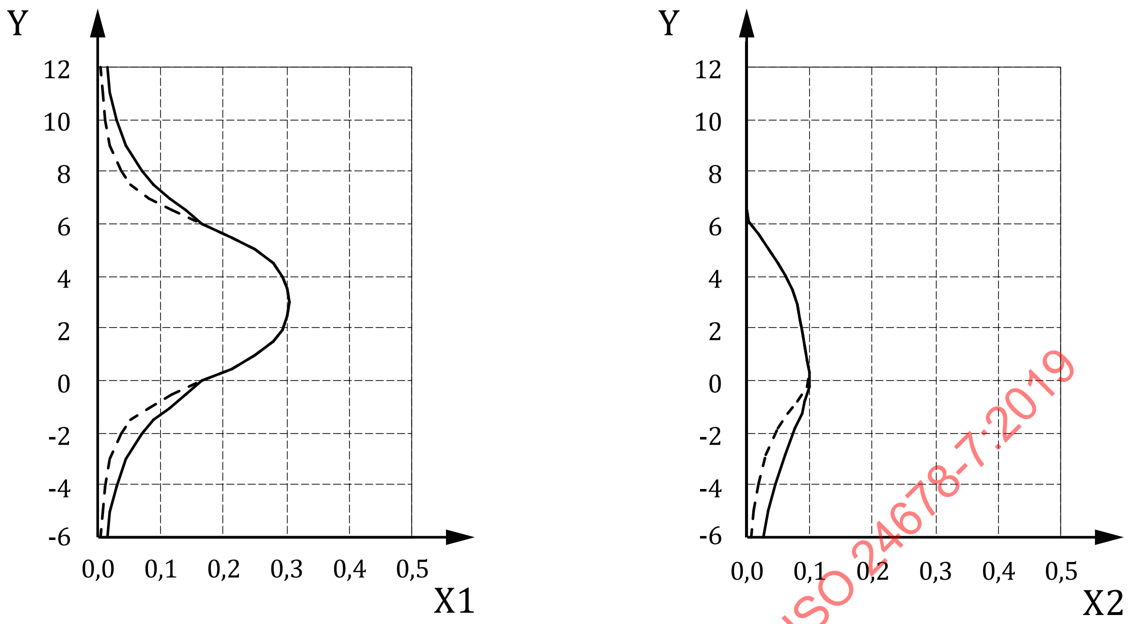
1 flame

2 target on vertical or horizontal surface

Figure B.8 — Calculation of a configuration factor to a vertical or horizontal target above the flame top

B.3.1.6 Calculation examples

In the case of L/R = 6 and X/R = 3, the configuration factor is calculated in the range of height ratio H/R = −6 to 12. The results are plotted in Figure B.9. The maximum configuration factor appears at a vertical target facing the flame at the middle height of the flame, $H = L/2$.



a) **Configuration factor to a vertical target** b) **Configuration factor to a horizontal target**

Key

X1 configuration factor to a vertical target, F_v

X2 configuration factor to a horizontal target, F_h

Y non-dimensional height of target, H/R

—— configuration factor of all surfaces including side, top and bottom surfaces

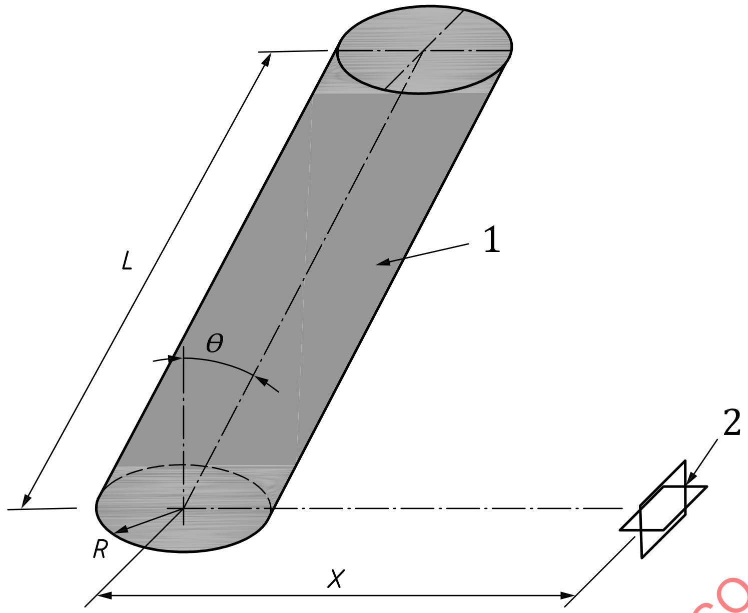
---- configuration factor of side surface only

Figure B.9 — Configuration factors of a flame to targets (L/R = 6, X/R = 3)

B.3.2 Configuration factor of a tilted flame to a target

B.3.2.1 Geometry to be considered

As shown in Figure B.10, the flame geometry is approximated by a cylinder of radius R and of height L. The flame is tilted by wind at an angle of θ in the direction downstream. The calculation formulae are shown for vertical and horizontal surfaces located downstream.



Key

1 flame

2 target on vertical or horizontal surface

Figure B.10 — Geometry of a tilted flame and location of a target

B.3.2.2 Target on the same height as the flame base

a) Vertical target facing the flame[24]

$$F_{\mathrm{v}} = f_{\mathrm{cyl}(\theta)\text{-v}}(l,x,\theta) \tag{B.18}$$

$$\begin{aligned} f_{\mathrm{cyl}(\theta)\text{-v}}(l,x,\theta) = \frac{1}{\pi}\Bigg[& -\frac{l\cos\theta}{x-l\sin\theta}\tan^{-1}\sqrt{\frac{x-1}{x+1}} \\ & + \frac{\cos\theta}{\sqrt{1+(x^2-1)\cos^2\theta}}\left\{\tan^{-1}\frac{lx-(x^2-1)\sin\theta}{\sqrt{x^2-1}\sqrt{1+(x^2-1)\cos^2\theta}} + \tan^{-1}\frac{(x^2-1)\sin\theta}{\sqrt{x^2-1}\sqrt{1+(x^2-1)\cos^2\theta}}\right\} \\ & + \frac{l\cos\theta}{x-l\sin\theta}\frac{l^2+(x+1)^2-2x(1+l\sin\theta)}{\sqrt{l^2+(x+1)^2-2l(x+1)\sin\theta}\sqrt{l^2+(x-1)^2-2l(x-1)\sin\theta}} \\ & \times\tan^{-1}\left(\sqrt{\frac{x-1}{x+1}}\sqrt{\frac{l^2+(x+1)^2-2l(x+1)\sin\theta}{l^2+(x-1)^2-2l(x-1)\sin\theta}}\right)\Bigg] \end{aligned} \tag{B.19}$$

b) Horizontal target facing upward[24]

$$F_h = f_{cyl(\theta)\text{-}h}(l, x, \theta) \tag{B.20}$$

$$\begin{aligned} f_{cyl(\theta)\text{-}h} = \frac{1}{\pi}\Bigg[& \tan^{-1}\sqrt{\frac{x+1}{x-1}} \\ & + \frac{\sin\theta}{\sqrt{1+(x^2-1)\cos^2\theta}}\left\{\tan^{-1}\frac{lx-(x^2-1)\sin\theta}{\sqrt{x^2-1}\sqrt{1+(x^2-1)\cos^2\theta}} + \tan^{-1}\frac{(x^2-1)\sin\theta}{\sqrt{x^2-1}\sqrt{1+(x^2-1)\cos^2\theta}}\right\} \\ & - \frac{l^2+(x+1)^2-2(x+1+lx\sin\theta)}{\sqrt{l^2+(x+1)^2-2l(x+1)\sin\theta}\sqrt{l^2+(x-1)^2-2l(x-1)\sin\theta}} \\ & \times\tan^{-1}\left\{\sqrt{\frac{x-1}{x+1}}\sqrt{\frac{l^2+(x+1)^2-2l(x+1)\sin\theta)}{l^2+(x-1)^2-2l(x-1)\sin\theta)}}\right\}\Bigg] \end{aligned} \tag{B.21}$$

B.3.2.3 Target at other heights

For the targets at other heights, Formula (B.19) or (B.21) are superimposed in the same way as in B.3.1.

B.3.2.4 Calculation examples

Let the radius of the flame be R =1 m, the flame height be L = 6 m. The flame tilt angle is 30° in the direction toward the target. The configuration factors to a vertical and horizontal targets located at X = 4 m from the flame axis are calculated.

Non-dimensional flame height:

$$l = L / R = 6 / 1 = 6{,}0 \tag{B.22}$$

Non-dimensional horizontal distance:

$$x = X / R = 4 / 1 = 4{,}0 \tag{B.23}$$

$$\sin\left(\frac{30}{180}\pi\right) = 0{,}5 \tag{B.24}$$

$$\cos\left(\frac{30}{180}\pi\right)=0{,}866 \quad (B.25)$$

The configuration factor to a vertical surface is:

$$\begin{aligned}F_{\mathrm{v}} &= f_{\mathrm{cyl}(\theta)\text{-v}}(6{,}0;4{,}0;30)\\ &=\frac{1}{3{,}14}\left[-5{,}20\times\tan^{-1}(0{,}775)+0{,}247\times(0{,}883+0{,}505)\right.\\ &\qquad\left.+5{,}12\times\frac{29{,}0}{5{,}57\times5{,}20}\times\tan^{-1}\left(0{,}775\times\frac{5{,}568}{5{,}196}\right)\right]\\ &=\frac{1}{3{,}14}(-3{,}43+0{,}34\ 4+3{,}608)\\ &=0{,}168\end{aligned} \quad (B.26)$$

The configuration factor to a horizontal surface is:

$$\begin{aligned}F_{\mathrm{h}} &= f_{\mathrm{cyl}(\theta)\text{–h}}(6{,}0;4{,}0;30)\\ &=\frac{1}{3{,}14}\left\{\tan^{-1}(1{,}291)\ +0{,}143\times(0{,}883-0{,}505)-\frac{27{,}0}{5{,}57\times5{,}20}\times\tan^{-1}\left(0{,}775\times\frac{5{,}57}{5{,}20}\right)\right\}\\ &=\frac{1}{3{,}14}(0{,}912+0{,}198-0{,}647)\\ &=0{,}148\end{aligned} \quad (B.27)$$

B.3.3 Approximation by a rectangular emitting surface

B.3.3.1 General

The cylindrical flame is a precise presentation of the flame geometry for calculating the configuration factor. However, the calculation is complicated due to the nature of the cylindrical geometry. In practice, it is possible to approximate the emitting surface by a rectangular surface that covers the original shape.

B.3.3.2 Configuration factor of an upright cylindrical flame

B.3.3.2.1 Formulae

As shown in Figure B.11, the emitting surface is approximated by a rectangle. The effective width is calculated by the tangential lines drawn from the target centre to the flame base perimeter as lines t-a and t-b. By extending the lines toward a’ and b’, the effective radius of the flame is:

$$R_{\mathrm{e}}=R\frac{X}{\sqrt{X^2-R^2}} \quad (B.28)$$

As for the height, the line from the target to point c is extended to c’, the effective height is:

$$L_{\mathrm{e}}=L\frac{X}{X-R} \quad (B.29)$$

The configuration factors from the rectangular emitting surface to the target are[29]

a) Vertical target facing the flame

