ANALYSIS OF FIRE HAZARD AND SAFETY REQUIREMENTS OF A SEA VESSEL ENGINE ROOMS

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Abstract

This paper presents the results of research on fire hazard coordinated by the Fire Safety Subcommittee of the International Maritime Organization (IMO). On the basis of statistical data, it identifies the main sources and frequency of fires in engine rooms. It also presents calculations of frequency of fires caused by self-ignition of flammable liquids in fuel oil and diesel oil systems, which constitute 60% of the overall hazard. In the theoretical analysis (frequency calculation), changes in construction protection of systems as well as changes in safety equipment of adequate rooms, have been taken into consideration. Fire hazard identification has been conducted on the basis of statistical data of 73 fires of merchant vessels engine rooms out of the overall number of 6,000 vessels in the 13-year-long period of use.

As the final result of the research, fire prevention requirements for engine rooms and pumping stations have been developed. The requirements include, in particular: construction elements of systems preventing leakages with self-ignition, protection of ignition sources ('hot spots'), and ensuring safe engine room atmosphere. The results of the experiment have confirmed the possibility of conducting fire hazard quantitative assessment (estimation), the reliability of which is limited because of the nature of the model. As far as quality is concerned, results of risk sensitivity analysis confirm the effects expected when using safety requirements applied creatively.

Keywords: analysis of fire hazard, safety of sea vessel

1. Introduction

At its 86th session in 2009, IMO Maritime Safety Committee approved fire safety requirements for engine rooms according to a document entitled "Recommendations for fire prevention in vessel engine rooms and pumping stations" [3]. After coming into force, the above mentioned requirements should be applied by designers, builders and users of vessels together with other IMO standard documentation. The final draft of requirements is a result of team work coordinated by IMO Fire Safety Committee conducted in correspondence groups and working groups consisting of research institutes, shipbuilding industry groups, classification societies and representatives of IMO Member States, i.e. Argentina, China, Denmark, France, Iran, Japan, Korea, Norway, UK, the USA, and Poland.

The regulations have been drawn up on the basis of a formal analysis of fire safety, in particular the identification of vessel fire hazard and so-called 'analysis of hazard sensitivity' involving theoretical research on the influence of construction factors on fire hazard. When creating regulations, the present state of technology in shipbuilding industry was also considered.

2. Analysis of engine rooms fire safety

The basic indicator used to assess construction fire safety of vessels is fire hazard expressed in frequency of fires considering the number of vessels (tonnage) and their useful life.
Typical measurable units include:
- the number of fires/year,

- the number of ship years or a number of fires/a ship year,
- the number of ton years/fire or the number of fires/a ton year.

Frequency of engine rooms fires is estimated to constitute 30-50% of the overall fire hazard, half of which concerns self-ignition in fuel oil and diesel oil systems [1, 4].

For the purposes of this work, the analysis of engine rooms fire safety included:
- identification of hazards concerning engine rooms,
- theoretical analysis of hazards concerning fuel oil and diesel oil systems.

2.1. Hazard identification

Fire hazard identification has been conducted on the basis of statistical data of 73 fires of merchant vessels engine rooms out of the overall number of 6,000 vessels in the 13-year-long period of use [6]. The following conclusions arise from the analysis of the data:

The frequency of fires in engine rooms during the period covered by the research is 1/1013 ship years, which is equal to 6 fires in a single year.

Approximately 75% of fires occurred on ships in motion, out of which 52% resulted in immobilization of a vessel.

Most of the fires were caused indirectly by the 'human factor', in particular by errors in engine room service and use.

No correlation between frequency of fires, the period of use of a vessel, and tonnage has been found. However, it has been observed that hazards in vessels subject to new regulations of the International Convention for the Safety of Life at Sea (SOLAS) have decreased.

Main sources (places of occurrence) of fires are fuel oil and diesel oil engine systems for which the total frequency of fires equals 1/1751 ship year (~60%), 25% of which are caused by diesel oil systems.

A direct cause of fires in fuel engine systems is leakage (pulverization) of fuel under pressure from damaged joints. At the same time, the most frequent causes of leakages are vibrations of the machine and system elements.

The research shows that during opening overflow joints in piston sections of injection pumps, the momentary values of fuel pressure are 80–150 MPa. During reverse flow the pressure has an impact on supply pipelines – 'low-pressure pipelines' (0.18 MPa). Fuel pressure changes (according to ignition cycles in cylinders), combined with the effect of supply pump overflow joint's operation, cause stress wave in pipelines with pulsation up to 10 MPa, and cavity. With partial engine load (40-60%), momentary values of pressure pulsation are 6–8 MPa. In medium- and high-speed combustion engines the momentary values in supply pipelines may exceed the nominal value 8-10 times. Under dynamic pressure conditions, mechanical vibration appears which may damage fuel systems' elements. In particular, it may cause fatigue cracking of pipelines which may result in fuel leakages. The range of pulverization and fuel drops diameter during system leakage depend on the pressure and outfall's section. The probability of flammable hydraulic mist occurring in the air (atomization) is bigger when the pressure is higher and the outfall's section is smaller. The probability of self-ignition also depends on the possibility of 'hot spot' occurrence in concentration area in the scope of combustibility.

Figure 1 presents a general breakdown of percentage share of fire sources in engine rooms.

2.2. Theoretical analysis of fire hazards in fuel oil and diesel oil systems

The theoretical analysis of fire hazards in fuel oil and diesel oil systems includes calculations of frequency of fires of various types in the context of changes in construction safety (risk sensitivity).
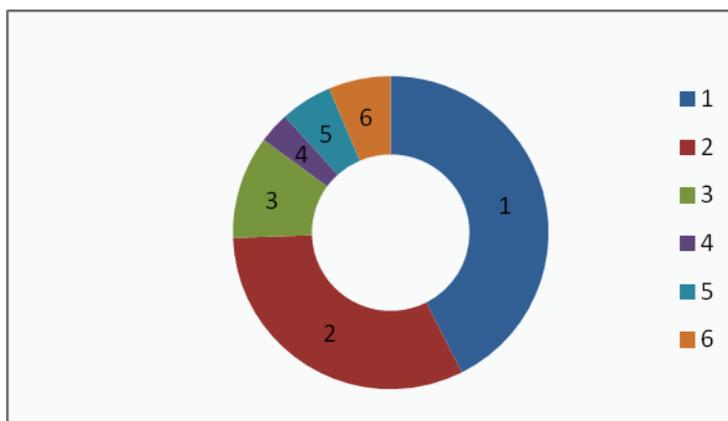
Fig. 1. Causes of fires in engine rooms where: 1 – fuel systems - 40%, 2 – lubricant oil systems – 30%, 3 – electrical systems - 10%, 4 – turbo compressors and exhaust gases piping -3%, 5 – waste oil systems (incinerating plants)-5%

2.2.1. General model of theoretical analysis

To analyze the fire hazard, a probabilistic calculation model has been used. It assumes the following scenario of events:
-   leakage of flammable liquid (damage of a system element),
-   interaction between flammable mixture and the ignition source,
-   ignition (fire occurrence),
-   fire detection (activation of fire detection system),
-   preliminary fire-fighting (use of portable fire-fighting equipment),
-   flammable liquid cut-off,
-   full scale fire-fighting (use of fixed fire-extinguishing system).

On the basis of statistical data [6], for the purpose of theoretical analysis of hazard the following has been taken into consideration: systems (machines) containing sources of potential flammable liquid leakage and sources of ignition.

There have been over 1000 potential leakage sources selected for identification, which included inter alia: pipeline joints, valves and accessories. They have been classified according to location in an engine room while taking into consideration factors affecting risks, i.e. their position and cooperation within a given system, outfall's sections and liquid temperature, distance from ignition sources, and safety equipment (equipment, fire-extinguishing and detection systems, leakage protection, thermal insulation, etc.) Engine room installations of a typical bulk carrier have been taken into consideration. Moreover, on the basis of statistical data general fire frequency of 5.71 x 10-4/ship year [6] has been adopted.

2.2.2. Results of fire frequency calculations

Table 1 presents results of summary calculations of relative fire frequency for fuel oil and diesel oil systems.

Tab. 1. Fire frequency for fuel oil and diesel oil systems

Systems	Frequency	
	Number of fires	Number of ship years
	[1/ship year]	[1/fire]
Fuel oil	4.04 x 10-4	2474
Diesel oil	1.67 x 10-4	6000
Total	5.71 x 10-4	1751

General frequency of fires in fuel oil and diesel oil systems is consistent with the statistical research results (p. 2.1).

Table 2 presents results of relative fuel oil and diesel oil fire frequency calculations for the main machines located in the engine room.

Tab. 2. Frequency of fires of main machines in engine rooms

Machine	Fire frequency 1/ship year	Share in general frequency
Main engines (fuel oil)	1.73×10^{-4}	0.3001
Main engines (lubricant oil)	8.58×10^{-5}	0.1492
Generator sets (fuel oil)	2.25×10^{-4}	0.3923
Generator sets (lubricant oil)	7.84×10^{-5}	0.1363
Boiler	1.04×10^{-5}	0.0181
Waste oil incinerating plant	3.79×10^{-7}	0.0006
Fuel tanks	1.82×10^{-7}	0.0003
Other piplines and machines	1.72×10^{-6}	0.0031
Total	5.75×10^{-4}	1.0000

2.2.3. Research on risk sensitivity
Sensitivity coefficient

Influence of construction factors (changes in safety equipment) on fire hazard has been expressed with the use of 'sensitivity coefficient'. Its value is calculated on the basis of the following formula:

$$C_f = \frac{F_+ - F_-}{F_o} \cdot \frac{1}{n}, \tag{1}$$

where:
F_o - relative fire frequency with the safety equipment according to the initial classification [1/ship year],
F_+ - relative fire frequency with more safety equipment,
F_- - relative fire frequency with less safety equipment,
$n = 2$,
$n = 1$ - for $F_- = 0$.

Calculation results

Table 3 presents results of calculation of risk sensitivity coefficient for various types of fires, for changes in the number of detectors (nw), fire extinguishers (ng) and nozzles of fixed foam systems (nd), for such model areas as power generator sets and a boiler.

According to the table, a bigger number of fire-extinguishers, detectors and nozzles causes an increase of probability of small fires and at the same time decreases probability of medium and large fires. The impact of the number of fire-extinguishers on risk sensitivity is much lower than that of the number of detectors and nozzles. Absolute value of sensitivity coefficient is bigger for areas of higher risk.

Tab. 3. Risk sensitivity coefficients for fires of a various scale and a various number of safety equipment

Risk area	Number of Safety Equipment			Small Fire		Medium Fire		Large Fire	
	nw	ng	nd	Fo 1/ship year	C f	Fo 1/ship year	Cf	Fo 1/ship year	Cf
Power generator sets platform	3 3 3 3+1	3 3 3+1 3	2 2+1 2 2	2.81x10-4	- 2.43x10-2 8.35x10-5 2.53x10-2	2.26x10-5	- -3.67x10-2 -1.23x10-4 -3.72x10-2	4.70 x 10-2	- 2.43x10-2 8.02x10-5 2.39x10-2
Boiler platform	1 1 1 1+1	2 2 2+1 2	3 3+1 3 3	8.75x10-6	- 5.88x10-5 1.16x10-2 5.88x10-5	1.98x10-6	- -8.65x10-5 -1.71x10-7 -8.65x10-5	2,19x10-7	- -5.65x10-5 -1.12x10-7 -5.65x10-5

where:

Fo – relative fire frequency for the initial amount of safety equipment (nw, ng, nd),

Cf – risk sensitivity rate (sensitivity for changes) nw, ng and nd (increase by 1).

3. General characteristics of fire prevention requirements in engine rooms

In order to decrease probability of fires caused mainly by self-ignition of flammable liquids, new fire safety requirements for engine rooms included in "The Recommendations" [1], complement general requirements under the 1974 SOLAS Convention. In particular, „The Recommendations" are oriented towards increasing fire safety of fuel oil and diesel oil systems, securing 'hot spots' (of surfaces), and ensuring safe atmosphere of rooms (in appliances).

3.1. Increase of fire safety of fuel oil and diesel oil systems

The basic requirement enabling an increase of fire safety of fuel systems in engines is to ensure tightness of pipelines under pressure pulsations generated by injection pumps. Contractors of systems are obliged to inform users about maximum (peak) values of pressure pulsations, which should not exceed 1.6 MPa at the outlet of injection pump sets.

In order to eliminate pipeline damages (leakages) caused by vibrations, apart from meeting ISO and classifications societies' requirements, it is recommended to install pressure vibration dampers in injection pipes, and to use injection pumps ensuring a fixed injection pressure.

Operating practice has shown that currently used mechanical pressure accumulators and gas compressors are subject to fatigue damages, and their responsiveness is prolonged [1].

Fuel oil system sets should be selected and assembled in consideration of a possibility for vibrations in injection pipes to appear. It is highly recommended to use flanged joints to ensure a proper preliminary tension of joint bolts.

In order to limit fuel oil and diesel oil dispersion caused by lack of tightness, at pressure exceeding 0.18 N/mm2, pipeline joints should be shielded in the vicinity of 'hot surfaces' (it also concerns centrifuge and fuel oil and diesel oil treatment systems). In engine supply systems, double-wall injection pipes with drain space and leakage signaling system are recommended.

In order to prevent leakages in elastic joints and elastic hoses, the following elements are recommended:

- constructions approval and pressure test certificates (every 5 years),

- adaptation of constructions for working conditions, i.e. temperature, pressure, mechanical load, properties of liquids, etc.,
- conditions for pipe installation, i.e. maximum length and radiuses of bending, curve angles, direction deviation, supporting structures,
- frequency and verification criteria for elastic hoses subject to replacement.

In tanks with flammable liquids (fuel oil, lubricant oil, heating oil, and hydraulic oil), it is recommended to use equipment preventing excessive pressure and temperature increase, and spill caused by lack of tightness or overflow. Such systems include, inter alia:
- systems signaling critical levels,
- overflow and ventilation pipes,
- systems signaling critical temperature (220°C),
- level gauges and testing devices, constructed according to the designs included in "The Recommendations" and requirements of classification societies.

In order to ensure tightness of other fuel system elements, such as filters, expansion compensators, measuring instruments, and pipelines fittings, construction approval by supervising institutions, pressure tests certificates, devices for dispersion reduction and drainage of leakages, adaptation for working conditions (vibrations and high temperature), appropriate assembly stresses, etc., are recommended.

For repair and service systems of fuel installations, it is recommended to include the following operations:
- execution of procedures according to 'checklists', especially in case of replacement of parts and assembly,
- coordination of installation (assembly) by 'a person responsible for it' who should ensure full implementation of project goals according to detailed design documentation,
- identification of vibrations, fatigue stresses of welded and hardened joints, and damages of elements, on the basis of recognized diagnostic procedures,
- periodic verification of preliminary tension of injection pipes' joint bolts (every 3 months),
- periodic verification of low pressure pipelines fittings (every 6 months),
- verification of threaded joints during every assembly.

3.2. Hot spot protection

In accordance with SOLAS Convention, 'hot surfaces' in an engine room (exceeding 220°C) should be thermally isolated. The isolation is approved by a supervising (classifying) institution. In particular, isolation of external surfaces of the following machines is recommended:
- outlet exhaust pipes,
- boiler burners housing and units,
- turbo compressors exhaust pipes and frames,
- bare metal friction parts,
- inert gas generators,
- incinerating plants,
- highly loaded electrical control panels for centrifuges and compressors, etc.

Apart from isolation, ventilation of the surrounding space is applied as well as water spray systems (Hi-Fog) for such machines as centrifuge boilers, fuel oil and diesel oil boilers, electrical boards and systems (wires).

The temperature in fuel oil and diesel oil tanks placed in the vicinity of boilers should not exceed 10o below the temperature of ignition agent. Boiler control systems should ensure automatic fuel cut-off in case of flame failure, and burner system interlock in case if fuel supply is turned on.

The temperature of electric supply elements and drive transmission elements (glands, bearings)

of flammable liquid pumps, should be constantly controlled through permanent electrical systems with sensors responding between 60 – 80o (with automatic pump turn-off).

In steam (electrical) boilers for flammable liquids, temperature and fuel failure control and signaling systems, and automatic supply switches (at 220°C).

In heating oil systems with combustion boilers, protection against uncontrolled emission and a potential steam ignition includes, inter alia:
- temperature sensors in tanks,
- emergency tank drainage,
- fire and explosive mixtures detection systems,
- water spray systems,
- high pressure in systems in order to lower ignition temperature,
- pipe tightness inspections and tests.

It is recommended to conduct hot surfaces identification and isolation checks periodically, with the use of thermographic cameras or laser thermometres with accordance to approved procedures.

3.3. Safe atmosphere

In order to ensure safe atmosphere of engine rooms (as well as inside 'hot machines') it is recommended to apply ventilation systems of capacity sufficient for safe dilution of flammable mixtures of gas and oil mist below 5% of lower explosive limit (LEL). The atmosphere should be controlled by fixed elements of flammable gas, oil mist and smoke detection systems. Sensors layout should take into consideration the characteristics of space ventilation. Detailed design guidelines in this scope have not been prepared yet because of the lack of data which can be drawn up on the basis of already advanced computer simulations [2].

Recommendations for ventilation and atmosphere control also concern rooms with power hydraulics and heating oil systems, and centrifuges.

4. Conclusions

The following conclusions have been drawn from the research:

According to statistical data, engine room fire hazard constitute about 30-50% of the overall vessel fire hazard, where about 60% of fires break out in fuel oil and diesel oil systems.

The main cause of fires of fuel oil engines is a damage of pipeline elements caused by vibration in injection systems and pipelines vibrations generated by the elements of power transmission system.

The theoretical fire hazard analysis presented in this paper is an example of experimental use of a probabilistic model to calculate frequencies of relative fires in fuel oil and diesel oil systems, which takes into account statistical data based on real fires. Calculations of frequencies of particular fire sources and risk sensitivity coefficient have been conducted with the use of an example of fuel oil and diesel oil systems in engine rooms of a typical bulk carrier.

The results of the experiment have confirmed the possibility of conducting fire hazard quantitative assessment (estimation), the reliability of which is limited because of the nature of the model. As far as quality is concerned, results of risk sensitivity analysis confirm the effects expected when using safety requirements applied creatively.

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