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Simulation modelling of a heat exchange process between the containerized cargoes

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ABSTRACT

The current research is focused on the simulation modelling of a heat exchange process between the cargo containers during their transportation by containerships. The relevance of the described topic is concerned with the issue of fire safety and cargo monitoring onboard container vessels, which is especially important during dangerous goods handling. A brief review of the existing studies on the subject of thermal processes' modelling, including infrared thermography, as well as of the methods used for simulations are presented. This study proposes the model of a heat exchange, which is implemented into a computer simulation aiming to provide the necessary material and instrumental basis for the further research applying the methods of a simulation modelling, namely, the usage of various sensors in terms of different cargo hold configurations, developing of the algorithms for data processing etc.

1. Introduction.

The demand for container transportation, which has grown significantly in recent years, has led to the building of ultra-large container ships (ULCS). Such type of vessels has a number of advantages, mainly economical ones, which are issue of high importance for ship and/or cargo owners, as container transportation occupies more than 90% of the non-bulk market [5]. In this way, ULSCs give an opportunity to reduce the costs for multi-vessel maintenance issues, reduce fuel expenses, re-organize port operations, etc. However, it should be noted that despite the inherent advantages, commercial concerns, such as reducing the number of crews on board, are often opposed to safety issues. Practically, in most cases the number of crewmembers onboard ULCS is equal to the number onboard Panamax container ship. According to the studies based on EMSA reporting data and a number of other publications presented in [2, 9], it is possible to conclude that, from the safety point of view, general design concepts of ultra-large container ships are based on the same principles as for smaller ones. Although such an approach was expected to perform in an effective way, the combination of mentioned factors may lead to a number of difficulties, e.g. an increase in the load on the ship's crews. The last may provoke a higher level of risk for emergency occurrence, namely, by growing the harmful influence of the human factor. In this way, the high level of workload extends to all areas of onboard activities, such as maintenance of the ship, including her equipment and mechanisms; monitoring and control of the safety issues connected to the transportation process, particularly, to the condition of the cargo, etc. Increased attention in this aspect is given to the specialized cargoes, such as refrigerated, oversized and dangerous goods (IMDG). It should be noted, that transportation of IMDG cargo carries inherent risks that may lead to the development of emergency situations, endangering not only the ship herself and/or her cargo, but also, what is more important, the human lives. According to [5], 58% of the thirty-six contributing factors in the twelve fire/explosion reports are related to the emergency actions on board during the emergency response, equipment failure and/or its installation/design, and incorrectly declared or completely missing information regarding dangerous goods. Although there are studies, such as [13], which are focused on the fire resistance of containers, their properties and suggestions

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for further improvements, etc., it is difficult to disagree with the fact that the safest method of fire-fighting is to prevent the occurrence at the roots. In this way, methods and/or principles of early fire detection should be incorporated and enhanced, where applicable, in order to manage an effective and early response to dangerous situations and their prevention.

2. Literature review and problem statement.

Thus, in order to design a new system and/or propose the enhancement of an existing one, the necessary and sufficient material and instrumental base shall be provided. There is a number of research, which are known on the subject of heat exchange modelling and simulation systems aiming to simplify verification procedures.

The work [6] presented a discussion of the basic design methods for two fluid heat exchangers using techniques of recuperators and regenerators, highlighting the usage of each method depending on the task. Analysis of modeling and simulation of heat transfer phenomena carried out in [17], drawing attention to the applied techniques and packages, including programming languages, Matlab, Simulink, Modelica, etc. for solving heat transfer-related problems of conventional and advanced processes.

Nowadays Computational Fluid Dynamics (CFD) methods can replace and/or complement many experimental methods. CFD simulations are carried out with traditional Reynolds - Averaged Navier-Stokes (RANS). However, for unsteady flow in general, wake flows or flows with large separation RANS is not applicable. For this type of flow, it is more appropriate to use Large Eddy Simulation (LES). Extended LES to high Reynolds numbers are called Detached Eddy Simulation (DES), Unsteady RANS (URANS), Partially Integrated Transport Model (PITM), Partially Averaged Navier-Stokes (PANS) or Hybrid LES-RANS, which are related to unsteady methods presenting a mixture of LES and RANS. Detailed results comparisons of CFD simulation, in particular URANS, LES, DES and modified DES - with enhanced z-diffusion modification with experimental data regarding the film cooling performance of a single inline inclined hole flow simulations with density ratio of 2.0 and blowing ratio of 1.0 are discussed in [20]. An analysis and comparison of experimental and CFD simulated presented in [3], where average errors on the heat exchanger did not exceed 20%. As per authors the behavior of fluids and heat transfer obtained were evaluated as expected. A new method for the conjugate heat transfer simulation to couple the URANS flow simulation with the steady thermal conduction in materials was introduced in [19]. Time Smoothing method was proposed to avoid accurate time averaging which requires exhaustive computer memory and works well to achieve the coupling between the URANS and the steady thermal conduction.

The research [14] provides an overview of various aspects of heat exchangers and highlights findings from several contributions, for example heat transfer surfaces in agitated vessels based on the determination of the heat exchange area; assessment of the current progress of topology optimization in the field of heat transfer and heat exchanger design; method for measuring the transient temperature of the flowing fluid in heat exchangers based on time-temperature changes of the thermometer, using the local polynomial approximation based on nine points allowing to determine quite accurately the first and second derivatives of a temperature.

Issues related to the thermal design of gas turbine blades were discussed and several heat transfer technologies were examined as well as typical methods for validating the thermal designs of gas turbine aerofoils outlined in the work [15], highlighting the importance of thermal validation process during the designed aerofoils. The study [10] presented a multi-physics simulation framework combining large-eddy simulation, Monte-Carlo solver with detailed radiative properties and a self-adaptive coupling procedure for conjugate heat transfer to compute accurately steady and unsteady components of the solid domain temperature. The resulting simulation is applied to a confined premixed swirling flame under atmospheric pressure to predict the wall temperature measured experimentally, showing satisfactory agreement of about 10% without radiation taken into consideration.

The basics of infrared thermography concepts and applications are described in the work [4], highlighting the advantages and disadvantages of the infrared condition monitoring program. Another review [8] introduced the working principle of the infrared thermal imager, the state of an application of processing technology, as well as the application of multi / hyperspectral infrared remote sensing technology. The basic image adjustment functions in thermal imaging systems are researched in the paper [21], providing the simulation algorithms of the image adjustment function of the thermal system by MATLAB. The application of thermal imaging for the driving simulator is performed in the research [16] to enhance the safety field of nighttime navigation, using Unity integrated development environment (IDE). High-temperature measurements simulation involving the infrared thermal imager with infrared radiation detection technology was carried out in research [1], proposed as an alternative verification method and showing satisfying results in terms of alcohol combustion experiments presented in the paper. Another relevant study [22] considers the detection ability of infrared thermographs in a high-temperature environment, namely the effective distance to the target object. The basis for thermal system simulation is outlined in the work [11], covering many different methods as well as their advantages and disadvantages depending on the set task.

Summarizing the above literature review, it could be concluded that the field of simulation modelling for temperature control of containerized cargo remains relevant for the survey. In this way, *the aim of the current study* is to prepare the necessary instruments and methods for further research on the improvement of the existing systems for monitoring the condition of containerized cargoes during their transportation by sea and fire safety on container ships. In this way, the current paper is focused on solving the following simulation modeling *tasks*:

- development of a model for the heat exchange process between cargo containers in the cargo hold of the container ship

at the first approximation;
- implementation of the designed heat exchange model into a computer simulation.

3. Material and Methods.

Initial conditions and general concept of cargo containers' heat exchange simulation while stowed in containership's cargo hold.

In order to form a model at the first approximation, as well as to avoid any additional issues that may arise during the construction of the simulation and outside the limits of the established task, requiring separate research, the following initial conditions have been defined:

- simulated containers should be set as empty,
- simulated cargo hold should be loaded only with 40-feet units to cover one cargo bay with only one cargo container in the direction along the ship.

The temperature field $T(x_i; \tau)$ is a set of temperature values over time and at all points of the calculation area, where x_i is the coordinate of the point, m; τ – time, sec. For the Cartesian system, the orthogonal coordinate x_i takes the form $x_i = x, y, z$. Depending on the number of coordinates, three-dimensional, two-dimensional, single-dimensional and zero-dimensional (homogeneous) temperature fields are distinguished. A temperature field that varies in time is called a non-stationary temperature field, and a field that does not change, respectively, is called a stationary one.

As the designed model is a three-dimensional one, it was decided to consider one three-dimensional temperature field as three single-dimensional ones in accordance with the respective coordinate axes to perform all necessary calculations within the framework of the set task.

There are three basic methods of heat transfer in nature: thermal conductivity (conduction), convection and thermal radiation (radiative heat exchange) [7].

Thermal conductivity (conduction) is a method of heat transfer by means of the interaction of microparticles of the body (atoms, molecules, ions and electrons in metals) at a variable temperature field. Thermal conductivity is carried out in solid, liquid and gaseous bodies and is absent in a vacuum. In solids, thermal conductivity is the only way of heat transfer.

Convection is a method of heat transfer by means of the movement of the fluid substance's macro volumes from an area with one temperature to an area with another one. At the same time, the fluid substance with a higher temperature moves to the region of low temperatures, and from the region of low temperatures to the region of high temperatures. In a vacuum, heat convection is also impossible. Convection of heat is always connected to conduction, since the macro volumes of the fluid consist of microparticles and exist unevenly in the space of the temperature field. Convective heat exchange is a heat transfer process by joint conduction and convection, and is no longer an elementary method of heat transfer.

Thermal radiation (radiative heat exchange) is a method of transferring heat in space, which is created as a result of the electromagnetic waves' expansion, the energy of which, when interacting with matter, turns into heat. In nature and in technologies, all three methods of heat transfer can occur simultaneously or in combination with each other. Such heat exchange is considered as a complex heat exchange.

The division of the general heat transfer process into the elementary phenomena (thermal conductivity, convection and thermal radiation) is mainly carried out from methodological considerations. However, despite the fact that in reality these phenomena are interrelated and often accompany each other, in practical calculations, the separation of such complex processes is not always possible and/or appropriate. Thus, usually the result of the cumulative action of individual elementary phenomena is attributed to only one of them. In this way, such a phenomenon will be considered as the main one, while the influence of the secondary ones is usually considered to affect only the quantitative characteristics of it.

Thus, when the ignition source is placed in one of the containers in the simulated cargo hold, the process of the heat transfer between cargo units may be divided into the following stages:

1. Heat transfer between the ignition source and the fluid inside of the container (air).
2. Convective heat exchange inside of the fluid (air).
3. Heat transfer between the fluid (air) and the container wall.
4. Heat transfer through the container wall.
5. Heat transfer between the wall and the environment (air).
6. Convective heat exchange inside of the fluid (air).
7. Heat transfer between the fluid and the wall of the adjacent container.
8. Heat transfer through the container wall.
9. Heat transfer between the wall and the fluid inside of the container (air).

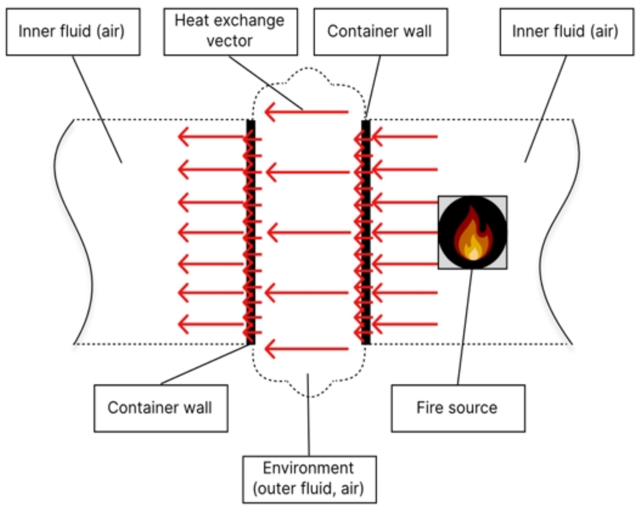
Simplified schematic diagram, visualizing the heat transfer process for one axis in front view projection of cargo containers, is brought to the Fig.1.

Heat exchange with the structural elements of the simulated cargo hold has not been taken into account within the framework of the set task. The stages from 2 to 9 should be repeated until the heat exchange process between the container units is completed.

In this way, the modelling of the described heat transfer process in order to achieve the established goal may be brought to the issue of the solving the "heat transfer through a plane wall" task, which commonly consists of:

a. Heat transfer from the hot fluid (in this case, air) to the respective plane wall (in this case, container side in the front and rear, left and right, top and bottom directions).
b. Conduction through the plane wall.
c. Heat transfer from the plane wall to the cold fluid (in this case, air).

Figure 1: Simplified schematic diagram of the heat transfer process between cargo containers (front view).



Source: Authors.

Consequently, in order to solve the task of the heat exchange within the set main objective stages 1 – 9 may be re-arranged into the three groups:

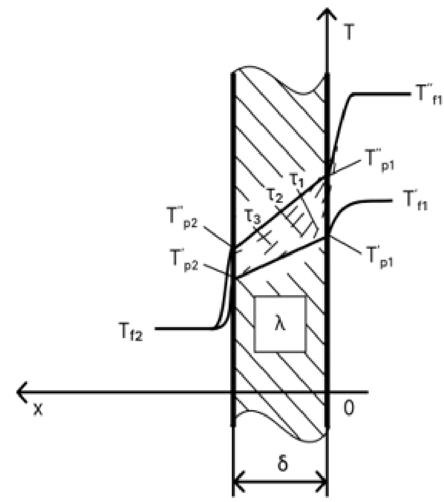
- heat exchange between the fire source and the first container's inner fluid;
- heat transfer through the wall of the first container;
- heat transfer through the wall of the second container.

As the temperature field of the described model changes within the time pass, so the heat exchange for each wall should be considered as the non-stationary process. Thus, in case when the temperature of the fluid is increased drastically, it may be described in accordance with the Fig.2, where: T'_{f1} – temperature of hot fluid at the initial stage, K; T_{f2} – temperature of the cold fluid, K; T'_{p1} and T'_{p2} –– temperatures of the wall's surfaces at the initial stage, K; T''_{p1} and T''_{p2} –– temperatures of the wall's surfaces at the final stage, K; T''_{f1} – increased temperature of hot fluid, K; δ – wall thickness, m; λ – thermal conductivity of the wall, W/(m ·K); τ_1, τ_2, τ_3 – time values of the respective dashed temperature curves [12].

At the initial stage the process may be assumed as stationary with T'_{f1} and T_{f2} – temperatures of hot and cold fluids respectively, and T'_{p1} and T'_{p2} –– temperatures of the wall's surfaces. If the temperature T'_{f1} is drastically increased until the value of T''_{f1}, then the process becomes non-stationary for some period of time (temperature curves at τ_1, τ_2, τ_3) until reaching the stationary state at the final stage.

The non-stationary heat exchange task may be defined by solving the differential heat conduction equation with the boundary conditions of the third kind in order to find the dependencies of temperature changes for any point of the body over the time frame.

Figure 2: Heat exchange through a container wall in a non-stationary state.



Source: Authors.

Differential equation of heat conduction in the context of mathematical basis for the cargo containers' heat exchange simulation

Boundary task of the heat conduction theory in the dimensionless view considering the boundary conditions of the third kind may be formulated as follows [12, 18]:

- differential heat conduction equation:

$$\frac{\partial \Theta}{\partial F_o} = \frac{\partial^2 \Theta}{\partial X^2} + \frac{k-1}{X} \cdot \frac{\partial \Theta}{X}; \qquad (1)$$

- initial condition:

$$\Theta_0 = \frac{T_f - T_0}{T_f - T_0} = 1; \qquad (2)$$

- boundary conditions:
  a. at the inner bound:

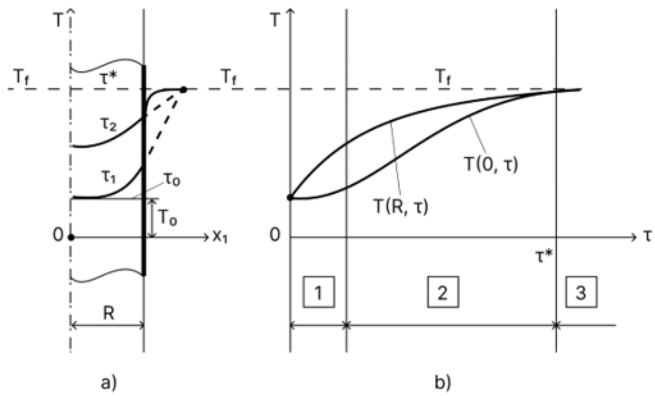
$$\left.\frac{\partial \Theta}{\partial X}\right|_{X=0} = 0; \qquad (3)$$

  b. at the outer bound:

$$\left.\frac{\partial \Theta}{\partial X}\right|_{X=R} = Bi \cdot \Theta_W, \qquad (4)$$

where:
$\Theta = \frac{T_f - T}{T_f - T_0}$ – dimensionless temperature; $X = \frac{x_1}{R}$– dimensionless coordinate; R – determining body size, m; $Bi = \alpha \cdot R / \lambda_p$ – Biot criterion; λ_p – thermal conductivity coefficient of a solid body, W/(m ·K); $F_o = a \cdot \tau / R^2$– Fourier criterion – dimensionless time; k – body shape coefficient; x_1 – the first coordinate in orthogonal coordinate system, $x_1 = x$ for Cartesian coordinate system, m; a – thermal diffusivity, m^2/sec; α – heat transfer

Figure 3: Temperature field considering the boundary conditions of the third kind.



Source: Authors.

coefficient, W/(m^2 ·K); τ – time of the process, sec; T_f - temperature of the medium, K; T_0 – initial temperature of the wall, K.

Temperature field in the process of a container's wall heating over the cross section and in time located within a medium with a constant temperature T_f and given heat transfer coefficient α is shown in Fig. 3: a) temperature's change over the container wall's cross section; b) temperature's change on the wall's surface and in its center over the time.

In this case, the heating (cooling) process passes the following three stages:

1. initial period which lasts until $F_o < 1/3k$;
2. regular period, commences from $F_o \geq 1/3k$;
3. state of the thermal equilibrium, that commences at the moment τ*, and at which the body temperature over the whole cross section becomes equal to the temperature of the body surface Tp.

Analytical solution for the boundary task of the heat conduction theory (1) – (4) was firstly obtained by Fourier and for the container wall (assumed as an infinite plate) may be presented as follows:

$$\Theta(X, F_0) = N_w \cos(\mu_1 \cdot X) \exp(-\mu_1^2 \cdot F_0), \quad (5)$$

where:

N_w – simple body shape coefficient; μ_1 – the first root of the characteristic equation for the differential heat conduction equation (1).

Temperature in thermal center (X = 0) and on the wall's surface (X = 1) for the regular period may be determined by the respective formulas:

$$\Theta(0, F_0) = N_w \exp(-\mu_1^2 \cdot F_0), \quad (6)$$

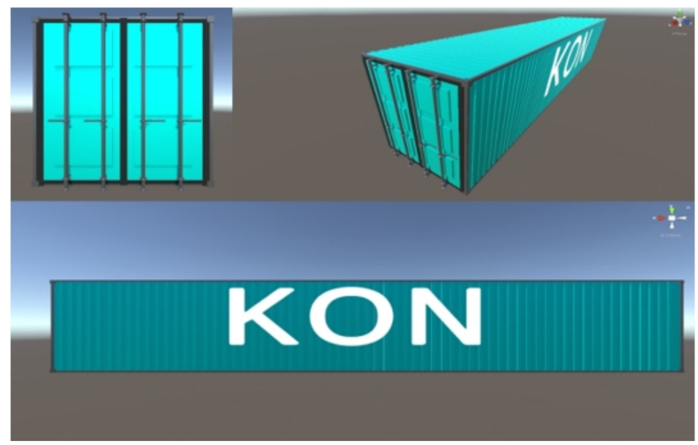
$$\Theta(1, F_0) = N_w \cos(\mu_1) \exp(-\mu_1^2 \cdot F_0). \quad (7)$$

Thus, considering the above, the heat exchange simulation has been created by means of Unity IDE and the capabilities of C# programming language.

4. Results of the heat exchange simulation modelling.

Simulation has been carried out using the methods of the object-oriented programming. Three-dimensional model of the 40-feet container has been designed together with the general arrangement of the container vessel's cargo hold at the first approximation. Cargo container's model is presented in the Fig. 4. Quantity of forty units is considered sufficient in order to carry out the research within the set framework.

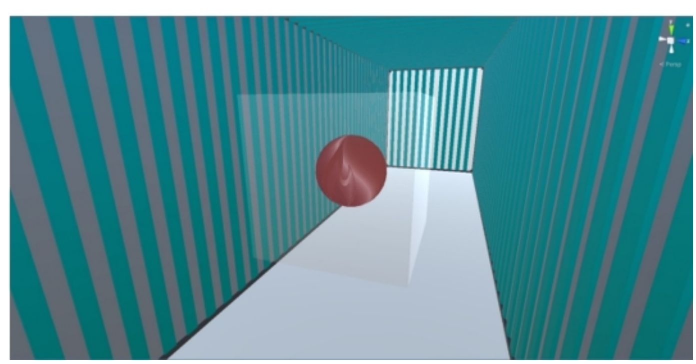
Figure 4: Cargo container's three-dimensional model.



Source: Authors.

Fire source is located inside one of the containers within the simulated cargo hold (Fig. 5). For the convenience of the model's application, its initial temperature value is set in degrees of Celsius.

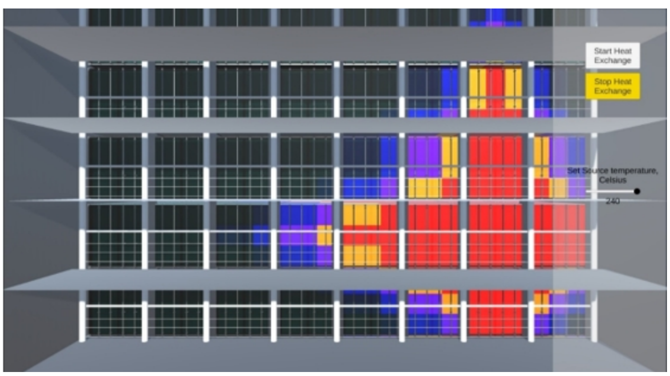
Figure 5: Fire source inside of a cargo container within the simulation.



Source: Authors.

Each side of the modelled container has a thermal layer, which is divided into several segments, which are able to change their color in dependence with their current corresponding temperature for the purpose of the process' visualization. In order to increase the performance of the application, and if limitations of the experiment allows, temperature dependency may be substituted to the linear one, considering the general algorithm described above. It may be useful, for example, in case when only the fact of the high temperature is required within the task. Heat exchange process within the developed simulation is presented in the Fig. 6. Designed model may be used for the further researches with the purpose of enhancing the existing and/or proposing new methods and systems for early fire detection and cargo temperature monitoring onboard the container vessels, using the advantages of simulation modelling. Namely, by solving the tasks: usage and allocation of sensors of various types; data processing algorithms, including implementation of digital neural networks; algorithms for fire source detection; etc. The model may be enhanced through the IDE with the necessary conditions and limitations of the future tasks, such as considering cargo hold configurations, e.g. bulkheads of the cross-decks, numbers of correspondent rows and tiers, etc.

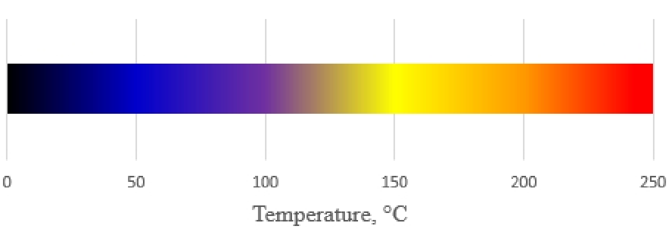
Figure 6: Heat exchange simulation between cargo containers (front view).



Source: Authors.

The color palette, which was used during the simulation, is presented in the Fig.7. Minimum and maximum temperature values that were applied for the simulation within the framework of the current tasks are 0 °C and 250 °C respectively. Set limits may be changed depending on the purpose of the further experiments.

Figure 7: Color palette for the heat exchange simulation.



Source: Authors.

Conclusions.

In the current research, the heat exchange model between the cargo containers inside of the container vessel's cargo hold has been proposed. It was implemented into a computer simulation at the first approximation with the methods of object-oriented programming by means of Unity IDE and C# programming language. The developed model is expected to be applied for further research as an instrument aiming to enhance the existing and/or develop new systems for early stage fire-detection and cargo temperature monitoring during their transportation by containerships. Such research may include, but not be limited to:

- application of various types' sensors, their allocation considering the specific cargo hold configurations;
- algorithms for the data processing, including the implementation of digital neural networks;
- algorithms for the fire source detection.

The designed model shall be modified in accordance with the required conditions and limitations of future tasks respectively in order to achieve the set aim.

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