GUIDANCE NOTES ON

THERMAL ANALYSIS OF VESSELS WITH TANKS FOR LIQUEFIED GAS

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Foreword

As the demand for liquefied gas containment systems increases, it is essential to consider the challenges associated with storing cargo at very low temperatures (e.g., cryogenic temperatures). Over the years, ABS has increased its understanding of liquefied gas containment systems and its many applications in the marine and offshore industries. These Guidance Notes provide procedures for heat transfer analysis of liquefied gas vessels or gas-fueled ships with membrane or independent types of tanks, consequent thermal stress analysis, and strength evaluation of independent tank and supporting structures to complement the rule requirements for gas vessels. Liquefied gas vessels include liquefied natural gas (LNG)/liquefied petroleum gas (LPG)/liquefied ethane gas (LEG) carriers, bunker ships, barges, Floating Storage and Regasification Units (FSRUs), and other offshore terminals.

The technical approach adopted in these procedures is based on heat transfer theory and finite element analysis. Temperature distributions in hull structures and supporting structures are employed for the selection of adequate material grades for construction and estimation of the boil-off-rate (BOR) during operation. The thermal stress analysis of independent tanks is performed under thermal loads due to temperature gradient in the tank structure under cooling down, partial filling, and full loading conditions.

These Guidance Notes are intended for use in conjunction with the requirements in Part 5C, Chapters 8, 12, and 13 of the ABS *Rules for Building and Classing Marine Vessels*, the ABS *Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks,* the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), and the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code).

These Guidance Notes become effective on the first day of the month of publication.

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SECTION 1 Introduction

1 General

With the increase in new cargo containment system designs, it is important to understand the role of thermal effects on the structural integrity of gas vessels and fuel tanks of gas-fueled ships that include the unique physical characteristics associated with very low temperatures (e.g., cryogenic temperatures). As defined in the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code), two major categories of liquefied gas containment systems in the gas market are addressed: membrane type and independent type. Independent type tanks include a further three subcategories of tanks referred to as Type A, Type B and Type C. These Guidance Notes will provide guidelines for:

- *Vessels with Membrane-type Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation.
- *Vessels with Independent Type A Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation.
- *Vessels with Independent Type B Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation; heat transfer and thermal stress analysis of tank structure is also performed for strength evaluation.
- *Vessels with Independent Type C Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation; heat transfer and thermal stress analysis of supporting structure is also performed for material grade selection and strength evaluation.

The membrane-type vessel is designed as a double hull structure with its cargo containment system attached to the inner hull. The membrane cargo containment system is composed of a primary barrier, primary insulation, a secondary barrier, secondary insulation, and mastics. The insulation prevents heat from transmitting into cargo tanks, and the primary membrane prevents direct contact between the insulation and the liquefied cargo.

If the primary membrane fails, the wetted primary insulation will lose its insulating functionality. In this case, the secondary barrier must maintain the integrity of the cargo tank for 15 days as per the requirements in the IGC Code. Thus, the inner hull should be designed to tolerate extremely low temperatures accordingly. If a regular grade of steel is employed for the inner hull at such a low temperature, the steel will become very brittle, and the structural safety of the vessel will be compromised. Therefore, temperature distribution analysis in this case should be performed to find the appropriate steel grades for hull plates.

In recent years, much attention has been paid to independent-type vessels in shipping and offshore applications. Independent tanks are completely self-supporting and do not form part of the hull structure. Moreover, they do not contribute to the hull strength of a vessel.

Independent tanks (which are usually made of cryogenic resistant materials such as aluminum alloy, nickel steel, or stainless steel) and their supporting structures (which are made either of steel or cryogenic resistant materials) are designed for liquefied gas vessels or fuel tanks for gas fueled ships. To prevent excessive thermal stress at critical locations in independent Type B cargo/fuel tanks with internal members such as stringers, girders, and stiffeners, it is essential to carry out FE heat transfer analysis and then thermal stress analysis to verify the strength of tank structures.

Boil off gas (BOG) is caused by heat ingress into the liquefied gas tank during the operation. The amount of BOG depends on the design and operating conditions of liquefied gas tanks and vessels.

1.1 Scope

These Guidance Notes denote procedures for heat transfer analysis, finite element (FE) heat transfer analysis, FE thermal stress analysis, and strength evaluation for liquefied gas vessels and gas fueled ships. Liquefied gas vessels include LNG/LPG/LEG carriers, bunker ships, barges, FSRUs, and other offshore terminals. These Guidance Notes provide an overview of steady-state heat transfer analysis methodology to estimate temperature distributions and corresponding heat transfer coefficients (HTCs) of hull structures in membrane or independent-type vessels under IGC or USCG environmental conditions. USCG environmental conditions for hull material selection are also applicable for non-US flag gas carriers (IGC Code applicable vessels) operating on the navigable waters of the United States and are not applicable to gas fueled vessels (IGF Code applicable vessels).

The estimated temperature distribution in both hull and void spaces can be employed for the steel grade selection of hull structures and the boil-off rate (BOR) calculation, and for further detailed FE analyses of tank and supporting structures in independent Type B and C vessels.

For membrane-type vessels, the temperature distribution of hull structure is calculated for material grade selection and the BOR calculation.

For independent Type A vessels, the temperature distribution of hull structure is calculated for material grade selection and the BOR calculation.

For independent Type B vessels, design thermal loads for various loading cases including cooling down, partial filling, and full loading are considered together with other mechanical loads to determine stress distributions from FE stress analysis. Finally, the stress distribution is used to evaluate the strength adequacy against yielding and buckling of tank structures.

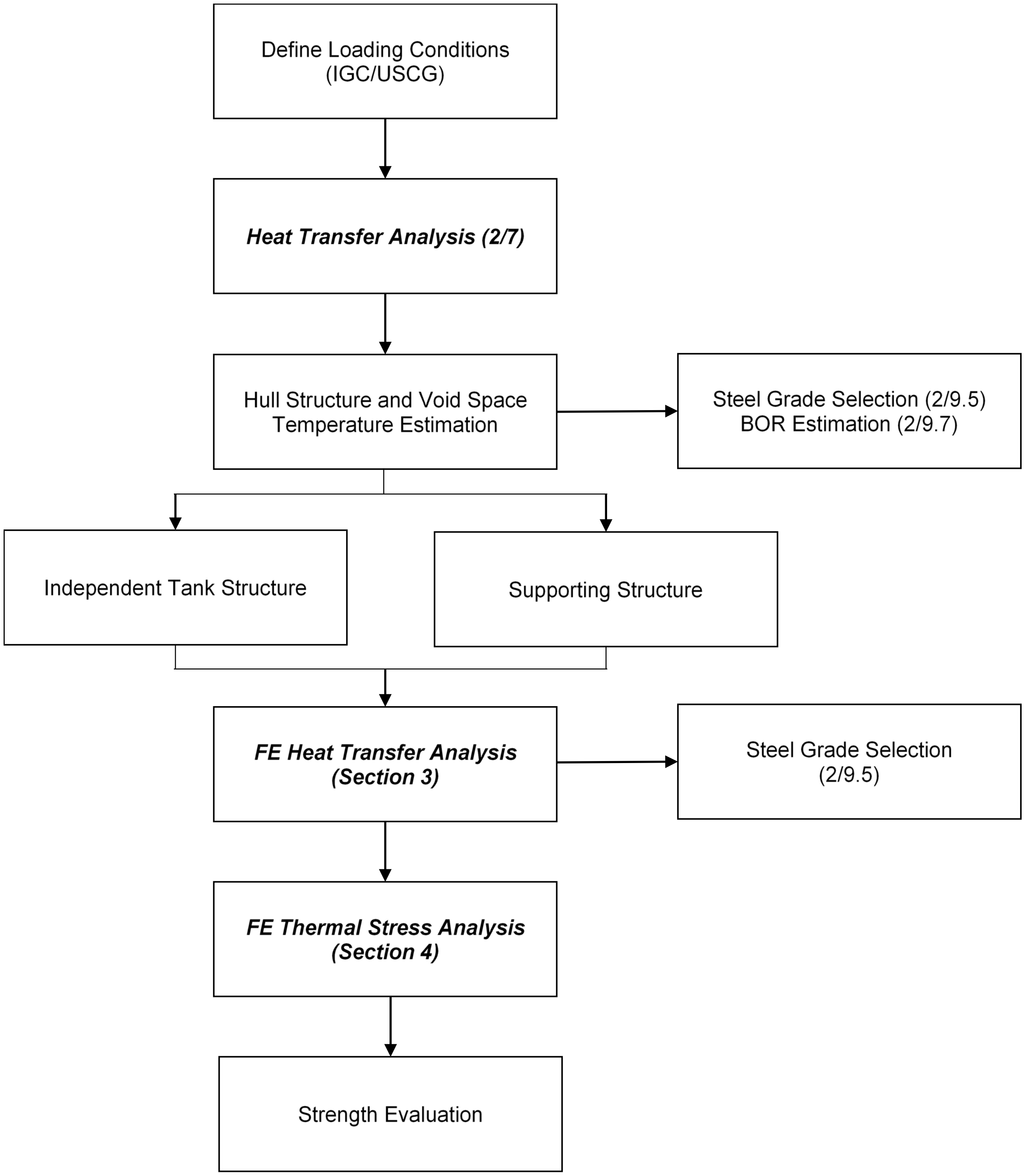
For independent Type C vessels, the detailed temperature distribution of supporting structures can be calculated to guide steel grade selection using steady-state thermal FE analysis based on estimated results. Stress distributions from FE thermal stress can be determined for strength evaluation.

Section 1, Figure 1 denotes the process for conducting heat transfer analysis, FE heat transfer analysis, FE thermal stress analysis, and strength evaluation.

1.3 Acronyms and Abbreviations

BOG	Boil-off Gas
BOR	Boil-off Rate
CFD	Computational Fluid Dynamics
FE	Finite Element
HTA	Hull Temperature Analysis
HTC	Heat Transfer Coefficient
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
LGC Guide	ABS *Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks*
USCG	United States Coast Guard

FIGURE 1
Heat Transfer Analysis, FE Heat Transfer Analysis, and FE Thermal Stress Analysis

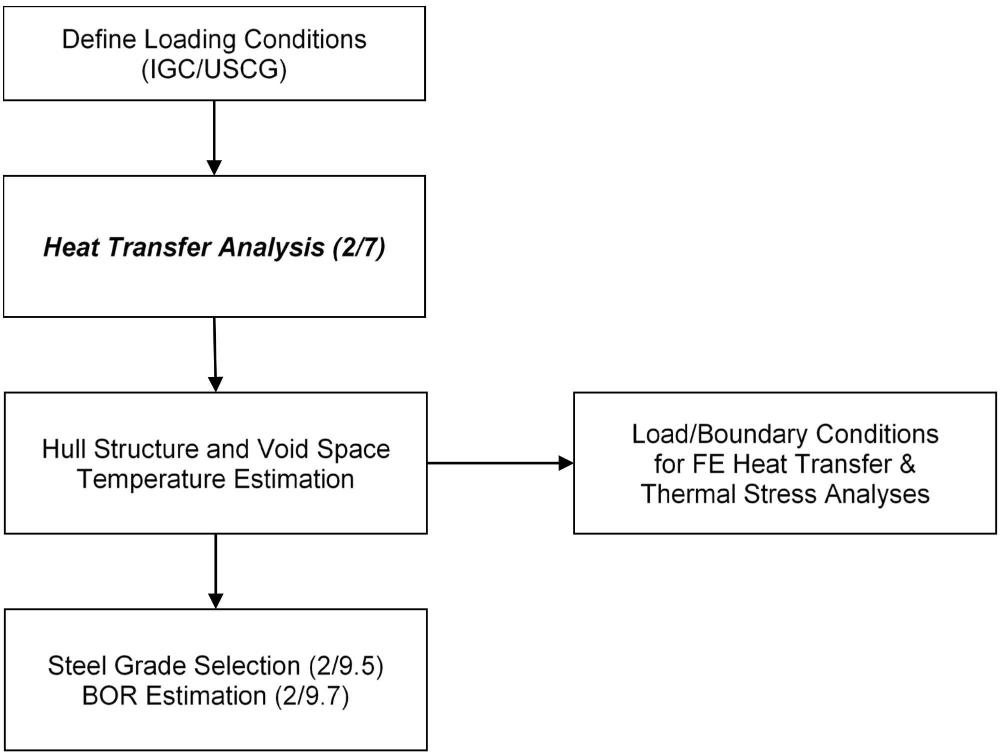


SECTION 2 Heat Transfer Analysis

1 General

Selection of the proper steel grade for the hull or surrounding structures is needed to satisfy the structural integrity of the vessel when exposed to very low temperatures. The boil-off gas (BOG) due to the heat ingress into the liquefied gas tank is an important factor during storage, transportation, and operations. The IMO IGC Code and the USCG requirements, which are incorporated in Part 5C of the ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)*, provide environmental conditions for gas vessel design, which can be used for heat transfer analysis. Section 2, Figure 1 denotes the process for heat transfer analysis, steel grade selection, and boil-off rate (BOR) calculation.

FIGURE 1
Heat Transfer Analysis Flowchart



3 Theoretical Background

The heat transfer analysis is derived from the law of conservation of energy, also known as the first law of thermodynamics. This law states that the total energy in an isolated system is constant. Energy can be transferred from one form to another but cannot be created or destroyed.

Heat transfer within a hull structure depends on thermal conduction, thermal convection, and thermal radiation. Each type of heat transfer results in a specific coefficient. This Section expands on these principles and provides a methodology to define their corresponding coefficients.

3.1 Conduction Heat Transfer

Thermal conductivity is a material property that reflects a material's ability to conduct heat. Because a temperature gradient exists in a stationary medium (either a solid or fluid), thermal conduction refers to the heat transfer that occurs across the medium. Conductive heat transfer can be expressed with "Fourier's Law" as:

$$Q_i = A_i \frac{k_i}{t_i} (T_{oi} - T_{ii})$$

where

A_i = area of heat contact

T_{oi} = outside surface temperature

T_{ii} = inside surface temperature

k_i = thermal conductivity of plate material

t_i = thickness of plate

The thermal conductivity of steel can be considered as a constant. The thermal conductivity of multiple insulation layers (e.g., plywood and foam layers) or plywood boxes with perlite can be considered as an equivalent value for the whole insulation system.

3.3 Convection Heat Transfer

Thermal convection is heat transfer due to the bulk movement of molecules within fluids such as gases and liquids. Convection heat transfer is classified into two types: free convection and forced convection. Free (natural) convection occurs when the flow is induced by buoyancy forces arising from density differences within the fluid. Forced convection is generally caused by external factors such as a fan or atmospheric wind of a ship moving through water. Therefore, the major heat transfer mechanism for the inner part of the hull structure of gas vessels is caused by free convection, while forced convection is the major heat transfer mechanism for the outer part of the hull structure.

3.3.1 Free Convection

The transition in a free convection boundary layer depends on the relative magnitude of buoyancy and viscous forces in the fluid. Its occurrence is generally correlated in terms of the Rayleigh number (*Ra*) and the Nusselt (*Nu*) number. The Rayleigh number is a product of the Grashof (*Gr*) number and the Prandtl (*Pr*) number. The Nusselt number (which is defined as a function of Rayleigh number) provides a measure of the convection heat transfer occurring at the surface. The Rayleigh number is expressed in the following equation:

$$Ra_L = Gr\,Pr = \frac{g\beta(T_s - T_a)L^3}{\alpha\nu}$$

where

Ra_L = Rayleigh number

Gr = Grashof number

$= \dfrac{g\beta(T_s - T_a)L^3}{\nu^2}$

Pr = Prandtl number

$= \dfrac{\nu}{\alpha}$

g = gravity acceleration

β = thermal expansion coefficient of the fluid at the film temperature

$= \dfrac{1}{T_f}$

T_f = $\frac{T_s + T_a}{2}$

T_s = surface temperature

T_a = fluid temperature

ν = kinematic viscosity of fluid at the film temperature

α = thermal diffusivity of fluid at the film temperature

And the Nusselt number is defined as:

$$Nu = \frac{hL}{k} = f(Ra)$$

where

L = characteristic length of the surface

k = thermal conductivity of the fluid

h = average convection coefficient of a surface of length L.

The temperature-dependent convection coefficient between surface and fluid (e.g., ambient air) is calculated based on the classical theories of free convection. It is assumed that the temperature of ambient air and surface, geometry of the surface, and thermal coefficient of the ambient air are known. These coefficients can be achieved by theory, experiment, or numerical method such as computational fluid dynamics (CFD).

The coefficient h can be also derived from the definition of the Nusselt number, which is a ratio of convective to conductive heat transfer across the boundary.

The correlation between the Nusselt number and Rayleigh number (described in the above sections) are summarized in the following four cases, as illustrated in Section 2, Figure 2 (see references 6 and 7):

i) Horizontal surface: $\theta = 0°$ and $T_s \le T_a$, or $\theta = 180°$ and $T_s \ge T_a$

$$Nu = 0.27\, Ra_L^{1/4} \qquad \text{for } 10^5 < Ra_L < 10^{10}$$

ii) Horizontal surface: $\theta = 0°$ and $T_s \ge T_a$, or $\theta = 180°$ and $T_s \le T_a$

$$Nu = 0.54\, Ra_L^{1/4} \qquad \text{for } 10^4 < Ra_L < 10^7$$

$$Nu = 0.15\, Ra_L^{1/3} \qquad \text{for } 10^7 < Ra_L < 10^{11}$$

iii) Vertical surface: $\theta = 90°$

$$Nu = \left\{0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + (0.492/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2$$

where the Prandtl number is defined as $Pr = \nu/\alpha$.

iv) Inclined surface: $30° < \theta < 90°$ and $T_s \le T_a$ or $90° < \theta < 180°$ and $T_s \le T_a$

$$g' = g \sin\theta$$

where g' replaces g for $Ra_L < 10^9$.

θ is the angle between the inclined surface and the horizontal plane, which is illustrated in Section 2, Figure 3.

Any additional condition that does not fall into the above categories is not covered by the classical heat transfer theory. Such cases should be studied individually.

FIGURE 2
Flow Characteristics in Horizontal Surfaces

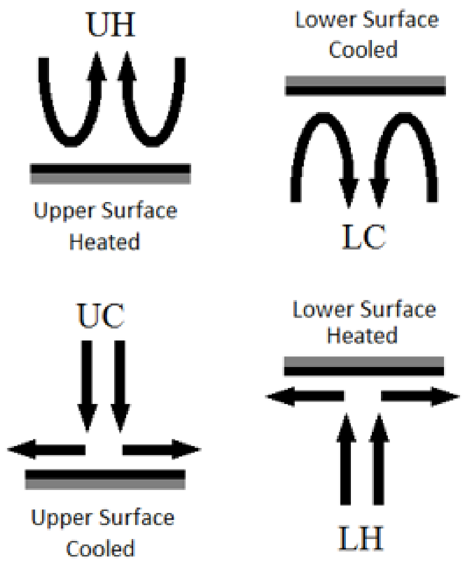
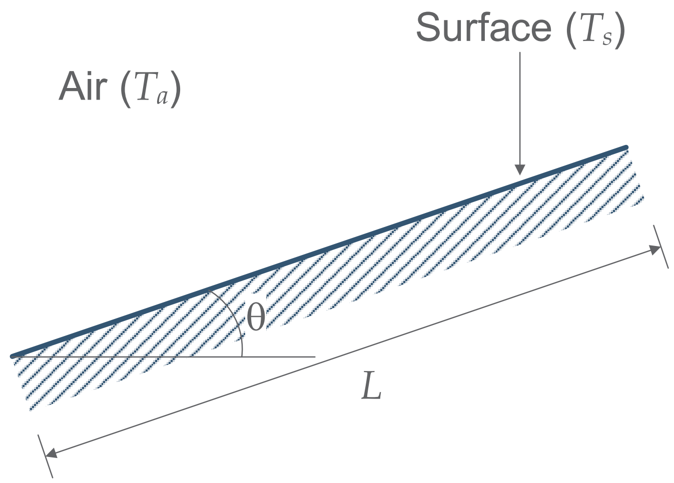


FIGURE 3
Heat Convection between Surface and Ambient Air



3.3.2 Forced Convection

In forced convection, the relative motion between the fluid and the surface is provided by external factors such as wind. Therefore, the heat transfer mechanism outside the hull strongly depends on the forced convection. The correlation of heat transfer between fluid and surface in the region of forced convection is considered for turbulent boundary layer as the following:

$$Nu = 0.037Re^{4/5}Pr^{1/3}$$

where

Re = Reynolds number

$= \dfrac{VL}{v}$

V = speed of the fluid

L = characteristic length of the surface

v = kinematic viscosity of fluid at the film temperature

Pr = Prandtl number, as defined in 2/3.3.1

3.5 Radiation

Thermal radiation refers to the heat transfer between two surfaces at two different temperatures. In the inner part of the hull, heat transfer depends on the free convection and radiation caused by the temperature difference between the two opposite walls. Generally, the effect of free convection on heat transfer fluctuates, but the radiation effect increases with increase of temperature difference between the opposing walls.

Thermal radiation is the emission of electromagnetic waves from all matter possessing a temperature greater than absolute zero. The radiation heat transfer with the surrounding environment given by the Stefan-Boltzmann Law is obtained by the formula:

$$Q_{ri} = A_i \varepsilon \sigma (T_{ei}^4 - T_c^4)$$

where

A_i = area of heat transfer

T_{ei} = environment temperature

T_c = compartment temperature

ε = emissivity factors

= 0.2 for steel

σ = Stefan-Boltzmann constant

The equation can be written in the following form:

$$Q_{ri} = A_i h_{ri} (T_{ei} - T_c)$$

The radiation heat transfer factor can then be calculated as:

$$h_{ri} = \varepsilon \sigma (T_{ei}^2 + T_c^2)(T_{ei} + T_c)$$

3.7 Heat Equilibrium Principle and Overall Heat Transfer Coefficient

Consider an arbitrary void space of the hull structure under heat transfer. The summation of heat flow into the inner void space and heat flow out to outer void spaces should be zero under steady state heat equilibrium, as illustrated in Section 2, Figure 4. The following equation shows the heat equilibrium equation of the void space, ignoring the effect of radiation:

$$\sum_{j=1}^{n} Q_j = 0$$

where

$$Q_j = U_j A_j \Delta T$$

where

U_j = equivalent overall heat transfer coefficient without radiation

$$= \frac{1}{\dfrac{1}{h_i} + \dfrac{1}{h_j} + \dfrac{t_j}{k_j}}$$

A_j = area of plate

h_i, h_j = convection coefficients of both sides of plate

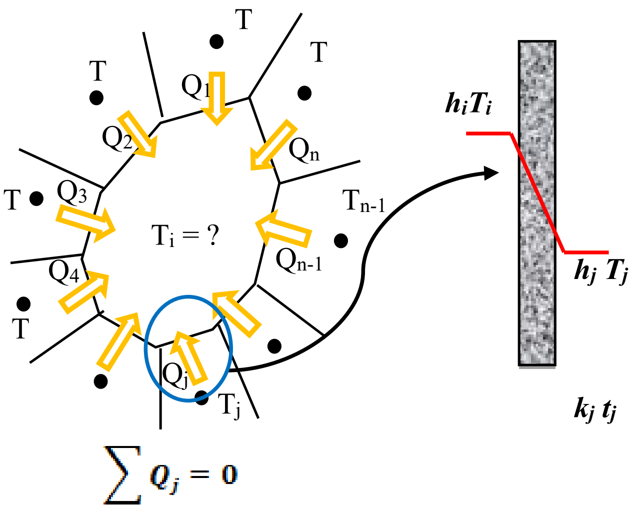
t_j = thickness of plate

k_j = thermal conductivity of plate

ΔT = overall temperature difference

= $T_j - T_i$

FIGURE 4
Heat Equilibrium of Void Space

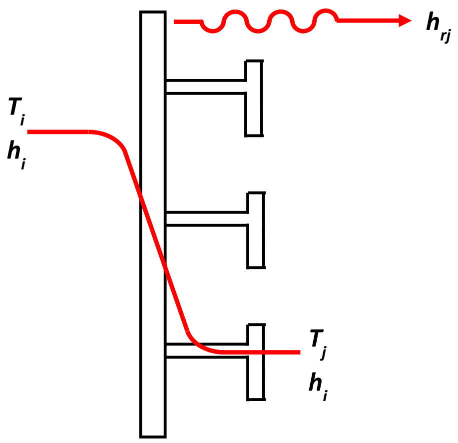


If the conduction, convection, radiation, and fin effect are considered together, as shown in Section 2, Figure 5, the overall heat transfer coefficient will be:

$$U_j = \frac{1}{\dfrac{1}{h_i} + \dfrac{t_j}{k_j} + \dfrac{1}{h_{rj} + mh_j}}$$

where m is the fin effect factor, which is defined in 2/3.7.1.

FIGURE 5
Fin Effect and Radiation



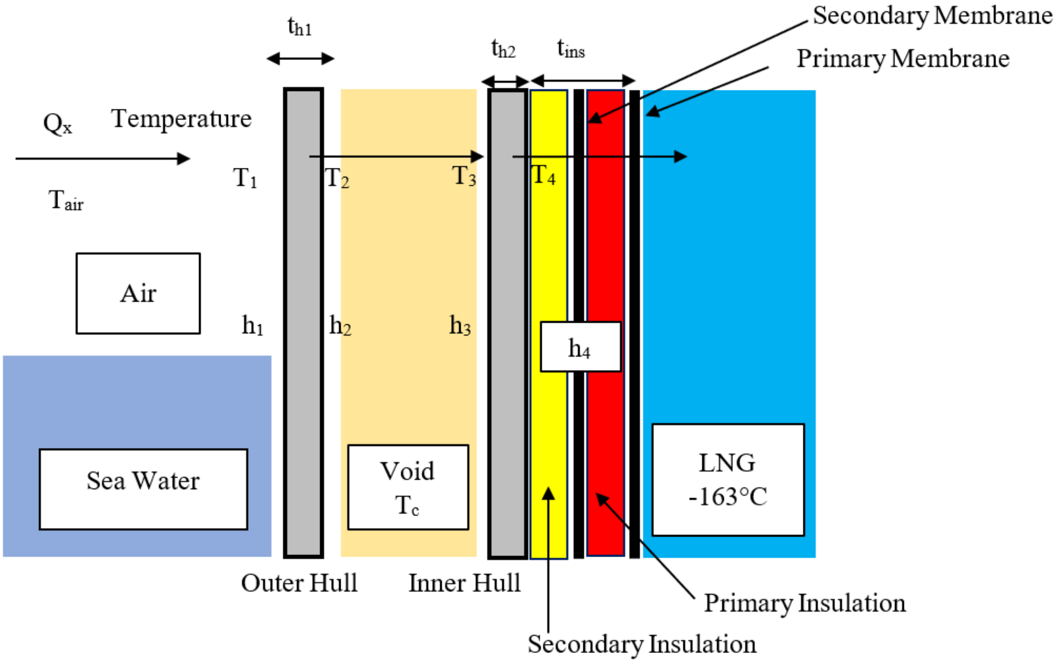
Section 2, Figure 6 shows an example of temperature gradient from external air/sea water outside the vessel to the LNG inside the cargo tank through the hull and the insulation for a typical membrane-type LNG carrier. In terms of energy conservation, assuming that the radiation and the fin effect are neglected, there is:

$$Q_x = (T_{air} - T_1)h_1A = (T_1 - T_2)\ \frac{k_j}{t_{h_1}}A = (T_2 - T_c)h_2A$$

$$= (T_c - T_3)h_3A = (T_3 - T_4)\ \frac{k_j}{t_{h_2}}A = [T_4 - (-163)]\frac{k_j}{t_{ins}}A$$

The plate temperature can be assumed to be the average temperature from the two surfaces of the steel plate. Usually the thermal conductivity for steel plates can be neglected except for the LNG insulation barrier.

FIGURE 6
Example Temperature Distribution of Double Hull with Insulation



3.7.1 Fin Effect

In hull structures, there are many stiffeners. The heat transfer rate of steel plate increases due to the presence of these stiffeners. This phenomenon is called the fin effect. In this analysis, the following assumptions are used:

i) Flat bar factor assumption

ii) Equivalent method

For a finned plate as shown in Section 2, Figure 7, the fin efficiency is defined as:

$$\eta_f = \frac{1}{mL}\frac{\sinh mL + (h/mk)\cosh mL}{\cosh mL + (h/mk)\sinh mL}$$

where

$$m^2 \quad = \quad \frac{hP}{kA_c}$$

k = metal thermal conductivity

h = bare surface convection coefficient

L = depth of the fin

w = width of the fin

t = thickness of the fin

A_c = $w \times t$

A_f = area of the fin

= $P \times L$

P = $2w + 2t$

The fin effect factor is calculated as:

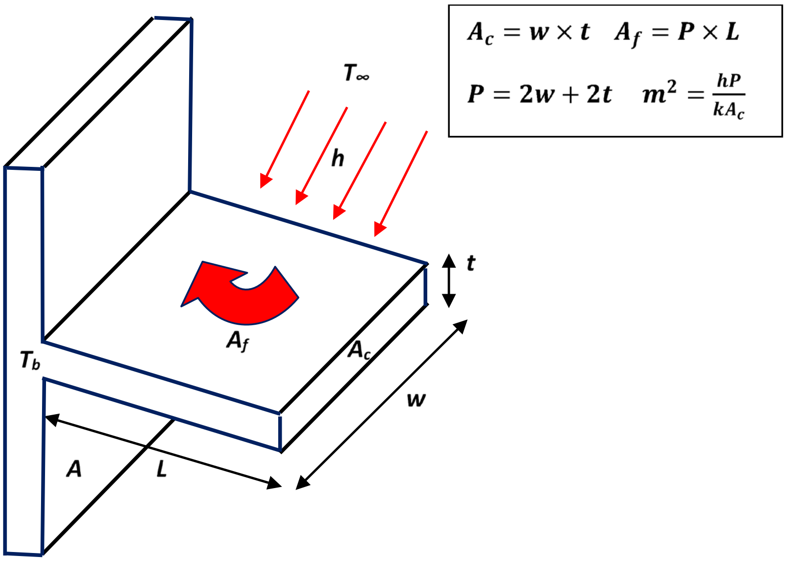
$$m = 1 + \frac{A_f}{A}\eta_f$$

where A is the area of the base plate.

The heat transfer coefficient considering the fin effect is calculated as:

$$h_{fin} = m \cdot h$$

FIGURE 7
Heat Transfer in Surface with Stiffener



3.7.2 One Dimensional Heat Transfer Model

The simplified one-dimensional heat transfer model is used as an input into a 2D or 3D analysis. The model considers each steel plate i in the compartment. Based on Fourier's Equation and Newton's Cooling Law, the equations of heat flow can be expressed as:

$$
\begin{aligned}
Q_i &= A_i h_{oi}(T_{ei} - T_{ioi}) \\
&= A_i \frac{k_{ioi}}{t_{ioi}} (T_{ioi} - T_{soi}) \\
&= A_i \frac{k_{si}}{t_{si}} (T_{soi} - T_{sii}) \\
&= m_{ii} A_i h_{ii}(T_{sii} - T_c)
\end{aligned}
$$

where

A_i	=	area of heat transfer
T_{ei}	=	environmental temperature
T_c	=	compartment temperature
T_{sii}	=	surface temperatures of steel plate, inside the compartment
T_{soi}	=	surface temperatures of steel plate, outside the compartment
T_{ioi}	=	cargo side surface temperatures of insulation layer
h_{oi}	=	convection coefficients of external environments
	=	convection coefficient of air/steel, if it is air in the environment.
	=	convection coefficient of water/steel, if it is water in the environment
	=	convection coefficient of cargo/steel, if it is cargo in the environment.
h_{ii}	=	convection coefficients of internal air
k_{si}	=	heat conductivity of steel plate
t_{si}	=	thickness of steel plate
k_{ioi}	=	heat conductivity of insulation layer
t_{ioi}	=	thickness of insulation layer, if it is installed
m_{ii}	=	fin effect factor

This equation can be further reduced into the form as:

$$Q_i = A_i U_i (T_{ei} - T_c)$$

while U_i is the effective convection coefficient and defined as:

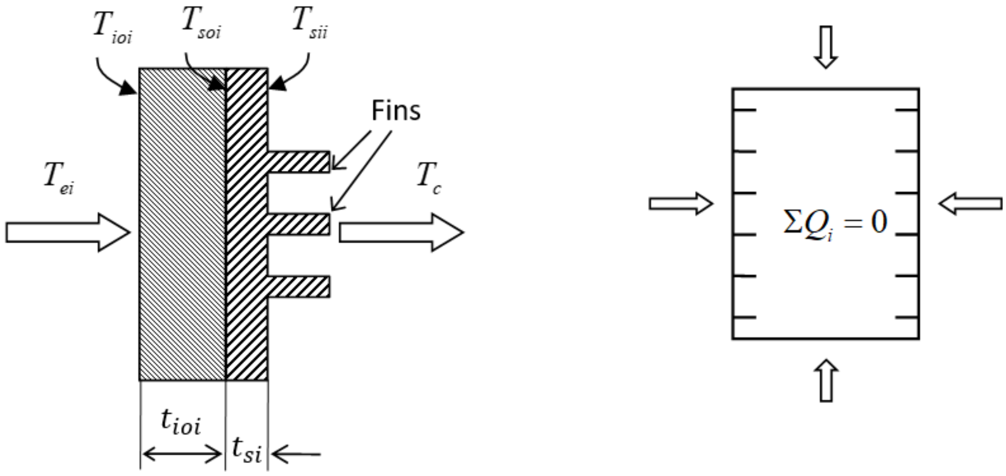
$$U_i = \frac{1}{1/h_{oi} + 1/m_{ii}h_{ii} + t_{si}/k_{si} + t_{ioi}/k_{ioi}}$$

For each compartment, the total heat flux should equal to zero:

$$\sum Q_i = 0$$

By solving the above equations, the hull temperatures can be calculated. Section 2, Figure 8 shows heat transfer through a plate and a compartment.

FIGURE 8
Heat Transfer for Steel Plates and Hold Spaces



5 Environmental Conditions

Environmental conditions specified by the IMO requirements for gas carriers should be taken into account for material grade selection, referring to 5C-8-4/19.1 of the *Marine Vessel Rules*. Different environmental conditions should be considered depending on the applicable Rules and purpose of the analysis. The United States Coast Guard (USCG) has additional design and structural requirements for non-US flag vessels operating on the navigable waters of the United States (see Appendix 5C-8-A2 of the *Marine Vessel Rules*).

Contiguous hull structure means hull structure that includes the inner deck, the inner bottom plating, longitudinal bulkhead plating, transverse bulkhead plating, floors, webs, stringers, and all attached stiffeners. As per the requirements of 5C-8-A2/3 of the *Marine Vessel Rules*, the contiguous hull material is to comply with 5C-8-4/19.1 and 5C-8-6/Table 1 through 5C-8-6/Table 5 of the *Marine Vessel Rules*, as applicable. The temperature studies required by 5C-8-4/8 of the *Marine Vessel Rules* should assume the ambient conditions specified in Section 2, Table 1 below.

TABLE 1
Environmental Conditions for Material Grade Selection

Requirement	*Air Temperature*	*Seawater Temperature*	*Wind Speed (knots)*
IMO: IGC Code	5°C (41°F)	0°C (32°F)	0
USCG excluding Alaskan waters (1)	–18°C (0°F)	0°C (32°F)	5
USCG including Alaskan waters (2)	–29°C (–20°F)	–2°C (28°F)	5

Notes:

1 Used in cases where the vessel is not designed to operate in Alaskan waters.

2 Used in cases where the vessel is designed to operate in Alaskan waters.

When determining the BOR for normal service, the upper ambient design temperature specified by the IGC Code conditions should be applied in accordance with Section 2, Table 2. Per the IGC Code requirements for service in particularly hot or cold zones, these design temperatures should be increased or decreased to the satisfaction of the Administration. The overall capacity of the system should be such that it can control the pressure within the design conditions without venting to atmosphere.

TABLE 2
Environmental Conditions for BOR Calculation

Condition	*Air Temperature*	*Seawater Temperature*
IGC Code	45°C (113°F)	32°C (89.6°F)

7 Heat Transfer Analysis Procedure

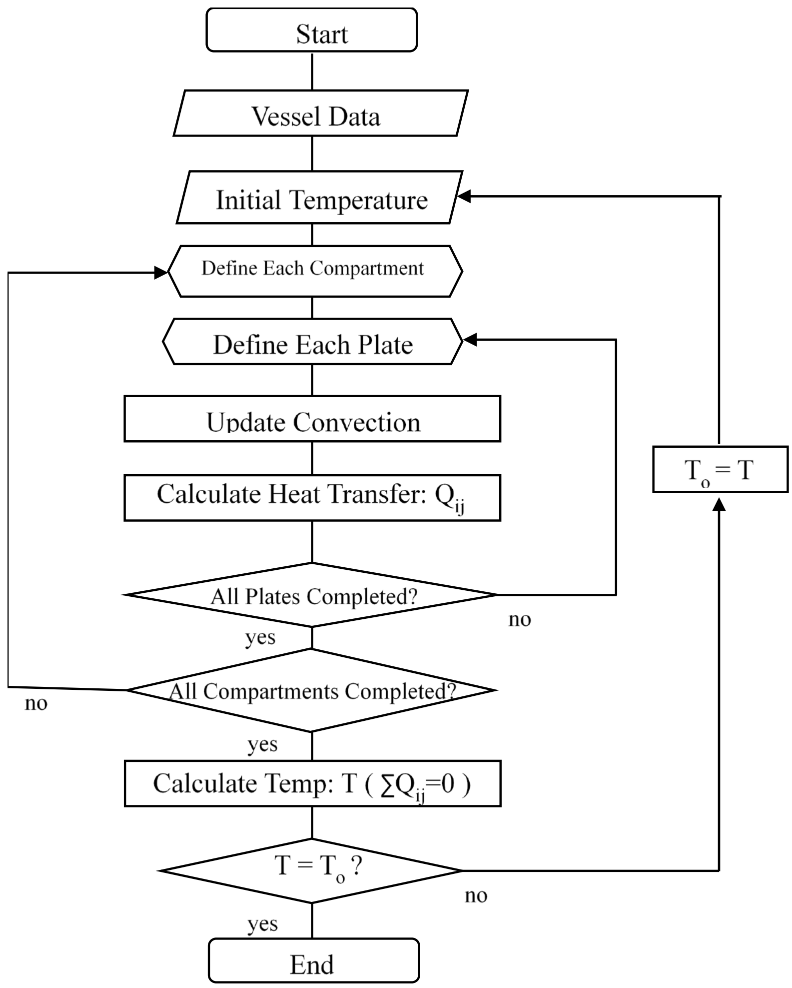
To customize the calculation for each individual vessel, the tank geometry of the specific vessel needs to be identified and dimensions and scantling data are input into the analysis model. For a symmetric problem, half of the geometry can be used to reduce the volume of calculation.

Environmental conditions such as air and sea water temperatures and cargo temperature need to be set before calculation. See Subsection 2/5 for specific conditions.

In the calculations of convection coefficients, the values of thermo-physical properties of the air such as conductivity, viscosity, and diffusivity are highly temperature dependent. Those values at a specific temperature can be approximated using linear interpolation.

Based on the above statement, the heat transfer analysis procedure is depicted in Section 2, Figure 9 to estimate the temperatures and corresponding heat transfer coefficients in void spaces and steel plates in hull structure, as well as to calculate the boil-off rate.

FIGURE 9
Heat Transfer Analysis Procedure



9 Applications of Heat Transfer Analysis

The heat transfer analysis described in this Subsection should be carried out to estimate the temperature distribution for the hull structure and the void space for gas vessels and gas-fueled ships. The results from heat transfer analysis can be used for the steel grade selection of hull structure or surrounding structure and the BOR estimation.

Two major categories of cargo containment systems are considered in these Guidance Notes: membrane and independent types of tanks. For example, a membrane-type of LNG vessel usually has a double-hull structure and an insulation system between the LNG cargo and inner hull. Vessels with independent tanks also have a double-hull structure, but the tank is independent of the hull structure, and the insulation system is located outside the tank.

The IGC and the USCG conditions (see Appendix 5C-8-A2 of the *Marine Vessel Rules*) are applied as environmental conditions of hull and tank structures for heat transfer analysis. The design considerations of membrane-type and independent-type vessels are listed in Section 2, Table 3, and the typical midship cross sections of different types of gas vessels with tanks are illustrated in Section 2, Figure 10.

TABLE 3
Design Considerations for Membrane-type and Independent-type Vessels

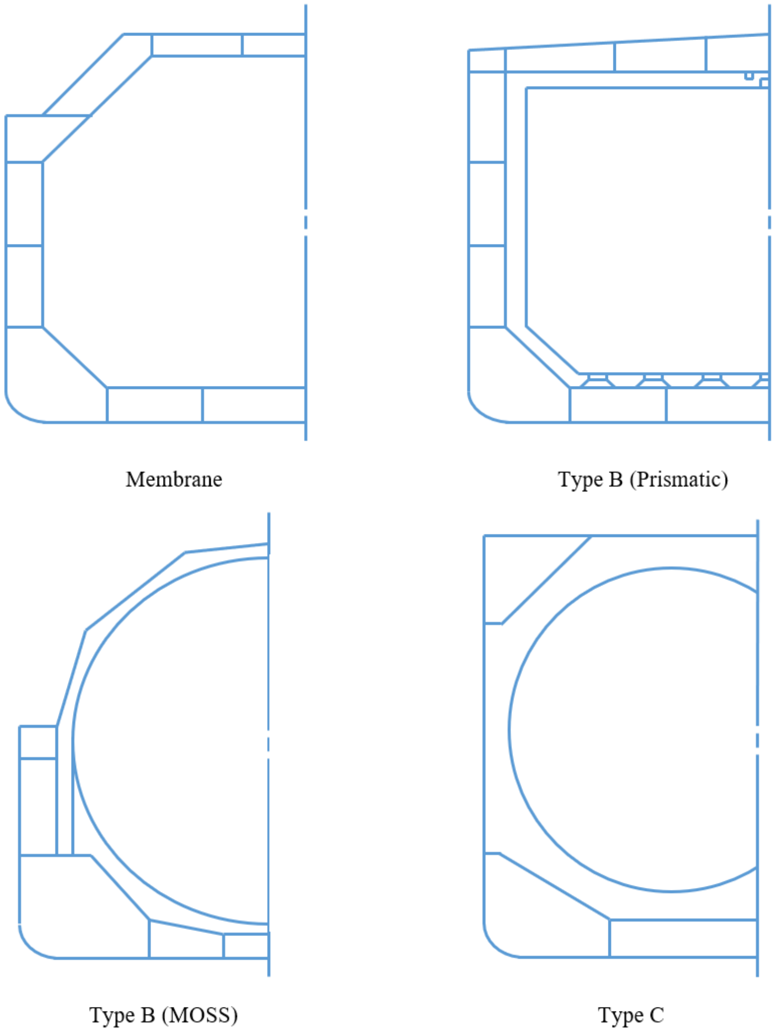
	Design Vapor Pressure Limit (kPa)	*Secondary Barrier Design*	*Design Approach*
Membrane	25 or 70*	Full secondary barrier	Systematic approach including analysis and tests
Independent Type A	< 70**	Full secondary barrier	Classic ship structure design rules
Independent Type B	< 70**	Partial secondary barrier	Model tests, analytical tools, and analysis
Independent Type C	> 200	No secondary barrier	Pressure vessel codes

Notes:

* The design vapor pressure limit can be increased to 70 kPa if appropriate design considerations are demonstrated.

** The design vapor pressure limit applies when the tank is primarily constructed by plane surfaces.

FIGURE 10
Typical Midship Sections of Gas Vessels



9.1 Membrane-type Vessels

Membrane tanks are non-self-supporting tanks and cargo containment systems consisting of a thin layer of metal (primary barrier), insulation, secondary membrane barrier, and further insulation in a sandwich construction. A fully redundant secondary membrane layer is designed to provide temporary containment of any envisaged leakage of liquid cargo through the primary barrier and to prevent the lowering of the temperature of the hull structure to an unsafe level in case of failure of the primary barrier.

For a membrane-type vessel, the damaged condition assumes that the primary barrier is damaged and the primary insulation is flooded but the secondary barrier and the secondary insulation remain effective. This damaged condition should be considered in the temperature distribution calculation based on the IMO IGC requirements.

Section 2, Figure 11 shows a typical membrane-type LNG hull structure, and the heat flux from outside into the inside of the double-hull tank is marked in the figure. For the calculation of heat convection coefficients, each plate of the cargo tank and its convection type should be defined as:

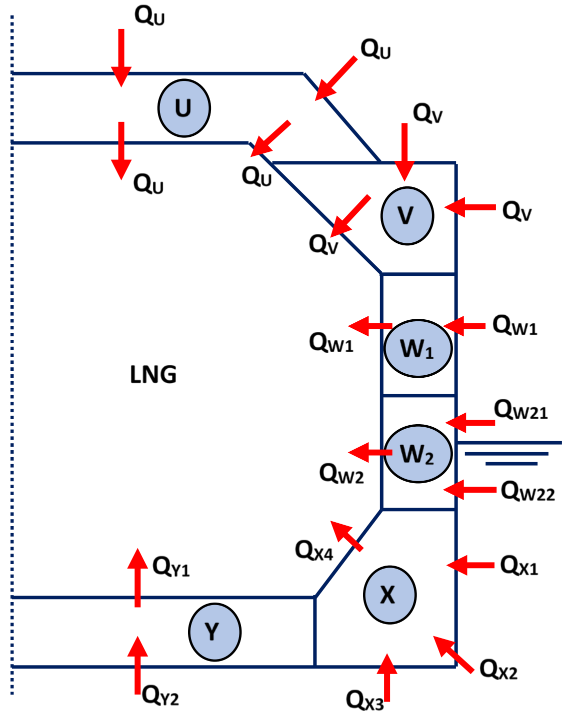
i) Convection type: free or forced

ii) Plate type: vertical or horizontal

iii) Adjacent fluid type: air, water, LNG.

External air and sea water flow in the form of forced convection. Air inside void spaces flows in free convection. For boundary conditions in the heat transfer analysis, assumptions are made based on the USCG and IMO conditions in Subsection 2/5. As an example, the temperature profile showing temperatures in plates and void spaces for a typical membrane-type vessel is given in Section 2, Figure 12.

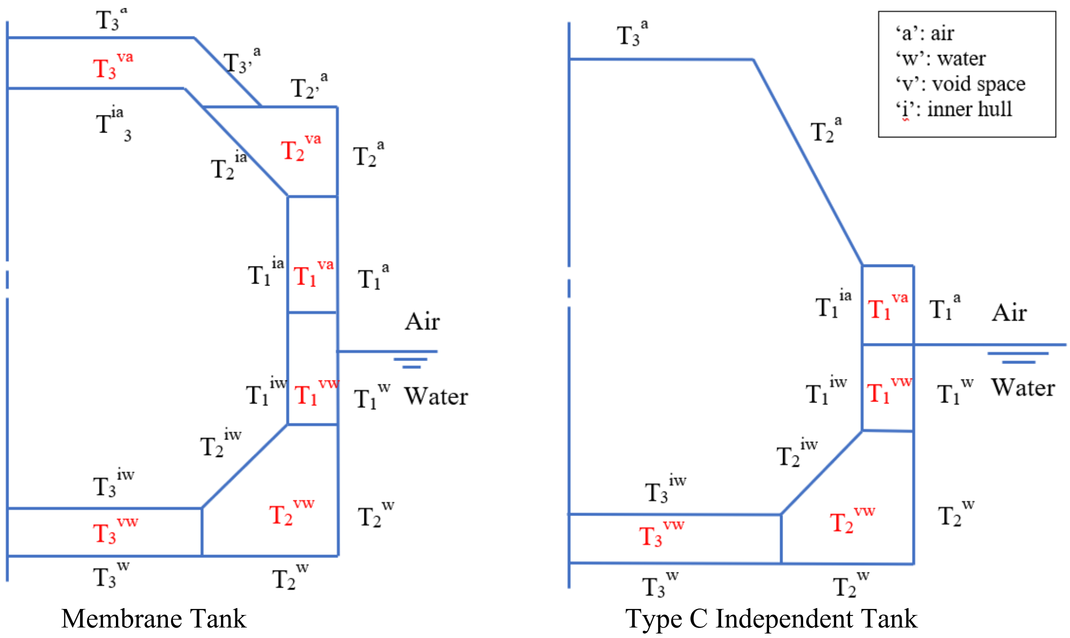
FIGURE 11
Schematic of Heat Flux in Membrane-type LNG Vessel



9.3 Independent-type Vessels

Independent-type vessels are self-supporting containment systems which do not form a part of the vessel's hull nor contribute to the hull strength. There are three categories of independent tank: Type A, B, and C. As an example, the temperature profile showing temperatures in plates and void spaces for a typical Type C vessel is given in Section 2, Figure 12.

FIGURE 12
Schematic of Temperature Distributions



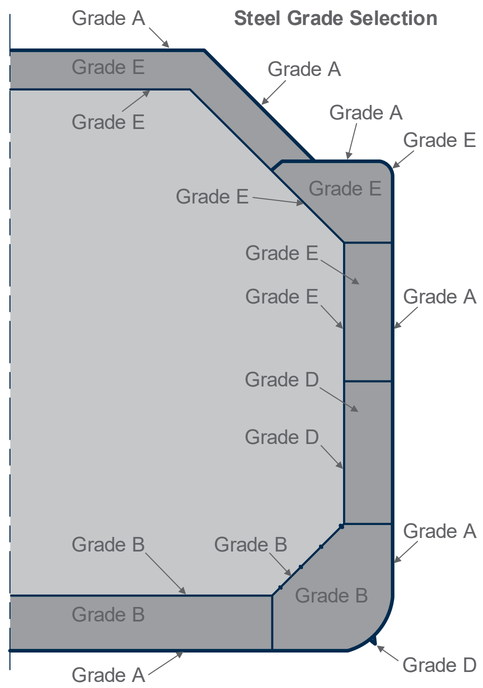
9.5 Material Grade Selection

The estimated temperature distribution results using the method described in this Section can be employed for the selection of an appropriate steel grade for the plates in the hull of gas vessels and for further detailed temperature distribution calculations using FE heat transfer analysis.

Material selection should be in accordance with 5C-8-6/Table 5 of the *Marine Vessel Rules* and the *IGC Code*. For vessels intended to carry liquefied gases operating on the navigable waters of the United States, the additional requirements in Appendix 5C-8-A2 of the *Marine Vessel Rules* should be followed for hull material selection.

As an example, the material grade selection for a membrane-type LNG carrier is given in Section 2, Figure 13.

FIGURE 13
Example of Material Grade Selection for Membrane-type LNG Carrier under USCG Condition for Inner Hull and IMO Condition for Outer Hull



9.7 Boil-Off Rate (BOR) Calculation

Many design factors should be considered in the design of a gas vessel because of the very low temperature of the cargo. The heat flux from ambient conditions into the inside of cargo tanks generates boil-off gas (BOG). This results in the pressure increase inside the tank and the boil off gas needs to be released to maintain the design pressure. Therefore, it is necessary to assess the BOR regarding the cargo tank insulation system.

With the assumption that all heat fluxes from outside into the inside of the cargo tank generate BOG, the daily BOR can be estimated by the following equation:

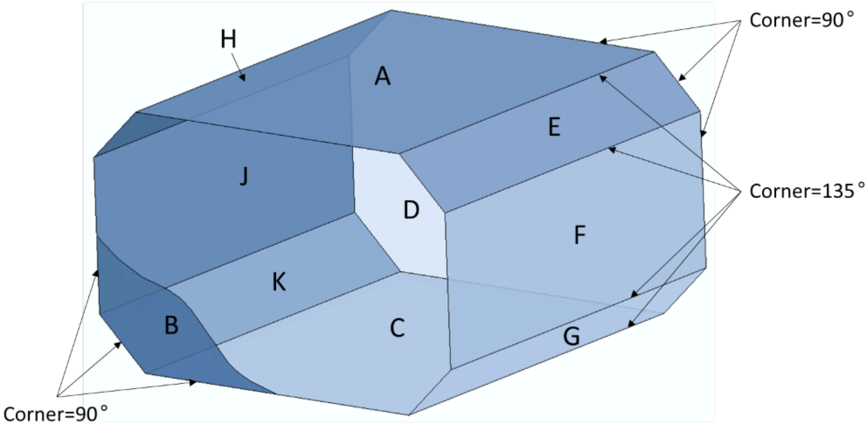
$$BOR = \frac{\sum Q}{\rho \cdot V \cdot H} \times 3600 \times 24 \times 100\%$$

where

$\sum Q$	=	total heat flux from outside to inside cargo tank
ρ	=	cargo density
V	=	cargo tank capacity
H	=	latent heat for vaporization

Section 2, Figure 14 gives an example for a tank with zone numbering in a membrane-type LNG carrier. The total heat flux from outside to inside the cargo tank, $\sum Q$, in the above equation should be the sum of all the local heat transfers corresponding to all the zones (A-K) including surface and corner areas. Each local heat transfer for a zone can be calculated following the equations in 2/3.7.

FIGURE 14
Example of Zone Numbering for a Membrane Tank



SECTION 3 FE Heat Transfer Analysis for Independent Tank and Supporting Structures

1 General

The objective of finite element (FE) heat transfer analysis for independent-type vessels is to calculate temperature distribution on independent tank and supporting structures. In Section 2, simplified heat transfer analysis can be done to determine the temperature distribution of hull structure. However, detailed temperature distribution analysis is still needed for independent tanks and supporting structures. FE heat transfer analysis involves the analysis of conduction and convection, which are the most common heat transfer mechanisms, to calculate the temperature distributions of the interested structural members. The results of the FE heat transfer analysis can be used to determine thermal loads (e.g., nodal temperatures) for the FE thermal stress analysis. It can also be used to further verify material grade selections of hull and associated supporting structures. A flowchart of FE heat transfer analysis for independent-type tanks and supporting structures is given in Section 3, Figure 1.

3 FE Model for Heat Transfer Analysis of Independent Tank and Supporting Structures

As stated in Section 2, the hull structure and void/cargo hold space temperatures as well as associated heat convection coefficients can be estimated using heat transfer theories. These estimated results can be applied as load/boundary conditions so that a detailed steady state heat transfer analysis can be conducted to determine the temperature distribution of the entire independent tank and supporting structure using finite element analysis (FEA) tools.

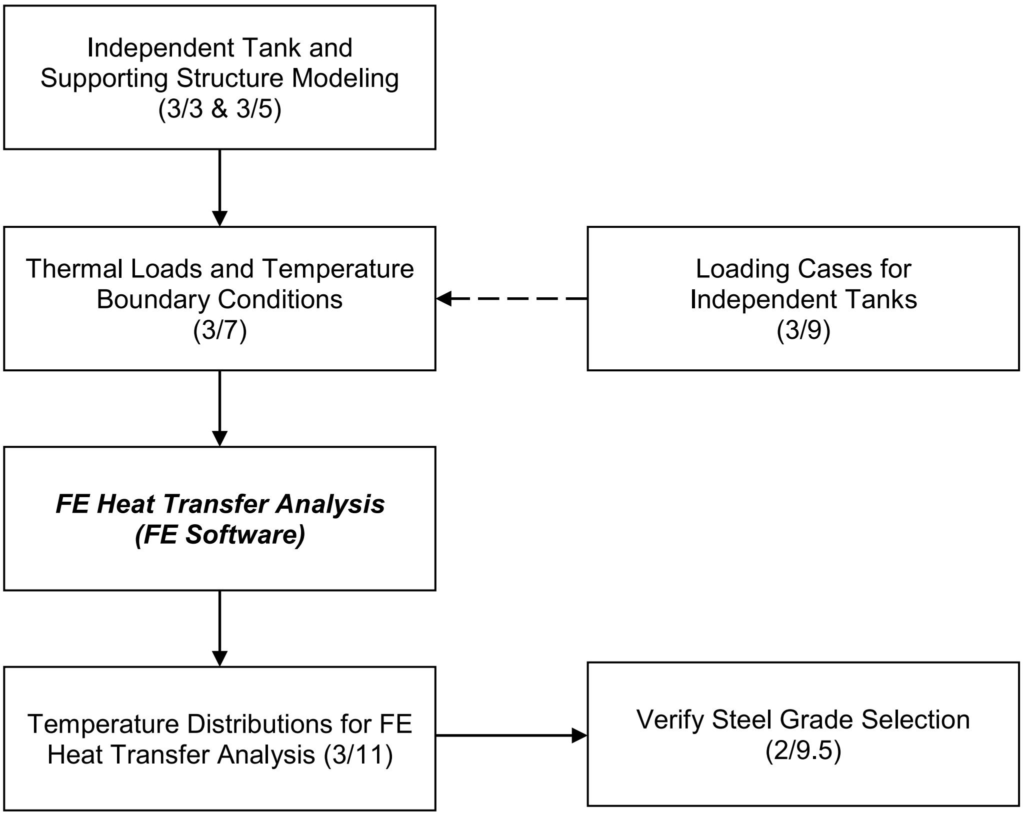
The FE heat transfer model may consist of the tank, the supporting structure, and/or the necessary associated hull structure. Suitable element types such as shell elements for the FE model are necessary for the heat transfer analysis. The element type needs a degree of freedom for temperature and should be able to account for thermal conduction and convection behaviors.

Thermal conduction coefficients should be specified for all structural members as their material properties (see Subsection 3/5). Thermal convection coefficients are given to those structural members which can gain or lose heat from or to the ambient atmosphere (see Subsection 3/7). In practice, the thermal radiation effect usually can be neglected if the insulation panel is used.

The available configurations for thermal loads and temperature boundary conditions are discussed in Subsection 3/7. For those tanks with internal stringers, girders, and stiffeners, there may be critical areas where local high stress concentration occurs due to a large temperature gradient. In this case, different loading cases, which include cooling down, partial filling, and full load, should be considered to calculate a detailed temperature distribution over all members for sequential FE thermal stress analysis.

FE mesh connection can affect heat and load transferring behaviors. For independent tanks, when the thermal insulation layer is placed between the cargo tank and supporting structure, or between supporting structure and hull structure, the interface can be modeled using a tie/glue constraint to represent the contact behavior across the surfaces.

FIGURE 1
Flowchart of FE Heat Transfer Analysis for Independent-type Tanks and Supporting Structures



5 Material Properties

For steady state FE heat transfer analysis, only the thermal conductivity coefficients are needed. The magnitudes of the coefficients should be selected in accordance with design temperatures.

7 Thermal Loads and Boundary Conditions

The types of thermal loading and temperature boundary conditions to be used in FE heat transfer analysis are as follows:

7.1 Convection Boundary Conditions

For main hull structural members such as the outer shell, inner hull, tank skin, and supporting structures, the convection coefficients and the associated ambient temperature are defined for each member.

7.3 Heat Flux Loads

If a heat sink and/or heat generator is installed on the liquefied gas vessel, the associated heat flux loads are used to reflect the heat transfer condition. Credit for hull heating may be taken in accordance with 5C-8-4/19.1.5 and 5C-8-4/19.1.6 of the *Marine Vessel Rules,* or 5C-13-6/4.13.1.1.3 and 5C-13-6/4.13.1.1.4 of the *Marine Vessel Rules*, if applicable.

7.5 Adiabatic Boundary Conditions

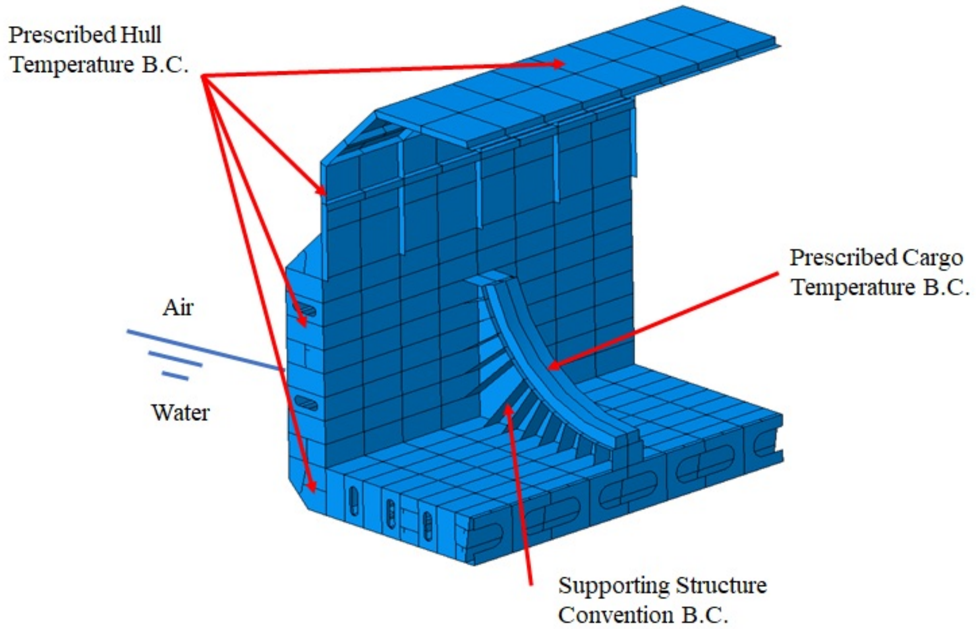
On any surface where neither thermal boundary nor thermal load is applied, the structural member is assumed to be perfectly insulated with no heat flowing through the surface.

7.7 Temperature Boundary Conditions

Temperatures are directly applied to the structural members such as transverse bulkheads in the cargo tank area and centerline bulkhead, etc., when the temperatures of these members are known and can be maintained unchanged or subjected to a prescribed profile. For those plates in contact with or immersed in the liquefied gas, the plate temperature is commonly specified as the cargo temperature. It is noted that, for steady state thermal analysis, the final heat flux equilibrium status is independent of the initial temperature, and therefore, it is not necessary to have an exact initial temperature for each member of the model.

An example of thermal loads and temperature boundary conditions applied to a Type C independent-type vessel with supporting structure is illustrated in Section 3, Figure 2.

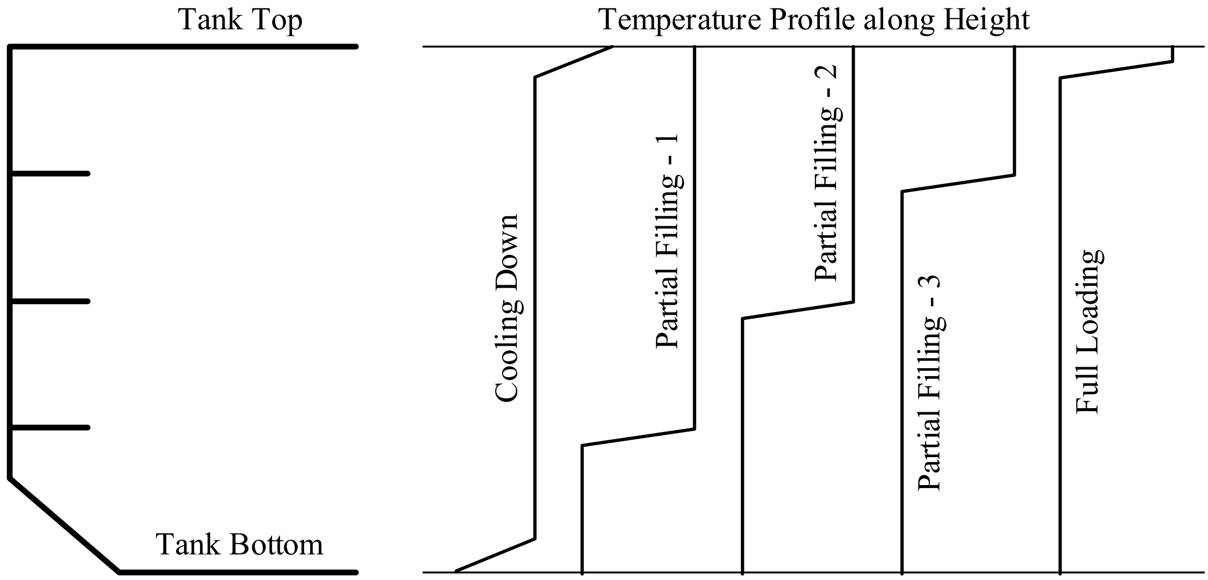
FIGURE 2
Example Configuration of Thermal Load and Temperature Boundary Conditions



9 Loading Cases

For independent tanks such as Type B prismatic tanks, there are internal stringers/girders and stiffeners intersecting the tank wall so that very high local stresses can occur due to the presence of high temperature gradients at critical connection locations. Thus, it is essential to assess temperature distributions under representative loading cases. Thermal loading produced by a temperature gradient from different filling levels of a tank should be considered. Filling levels up to each horizontal girder are considered separately. With reference to Appendix 5 of the ABS *LGC Guide*, the loading cases including cooling down, partial filling (at each stringer level (e.g., three filling levels around the stringers are shown in Section 3, Figure 3)) and full loading should be considered in heat transfer analysis. The schematic temperature profile for each loading case in an independent Type B tank is given in Section 3, Figure 3. For each filling level in this figure, the temperature gradient can be assumed to be a linear increase within a certain distance above the liquid surface.

FIGURE 3
Loading Cases



9.1 Cooling Down Case

An initial cool-down procedure is needed before liquefied gas at cryogenic temperatures can be introduced into the containment system. During this process, the liquefied gas is sprayed into the tank through nozzles, slowly decreasing the temperature in a process that takes hours to complete.

The cooling-down process of the containment system should be considered as an essential condition in terms of heat transfer (refer to the *LGC Guide*). The temperature gradient during the cooling-down procedure should be considered as the temperature on the tank decreases due to the initial quantity of sprayed liquefied gas that collects in the bottom of the cargo tank. During cooling down, attention should be paid to the bottom corner areas of the tank due to high temperature gradients in the vertical direction.

9.3 Partial Filling Cases

Partial filling conditions should be considered where the tank is filled with liquefied gas up to the height at each stringer/girder within the cargo tank, as depicted by the profiles of thermal gradient for partial filling-1, partial filling-2, and partial filling-3 in Section 3, Figure 3. The presence of stringers/girders can cause changes in geometry and lead to high stress concentrations at those intersections.

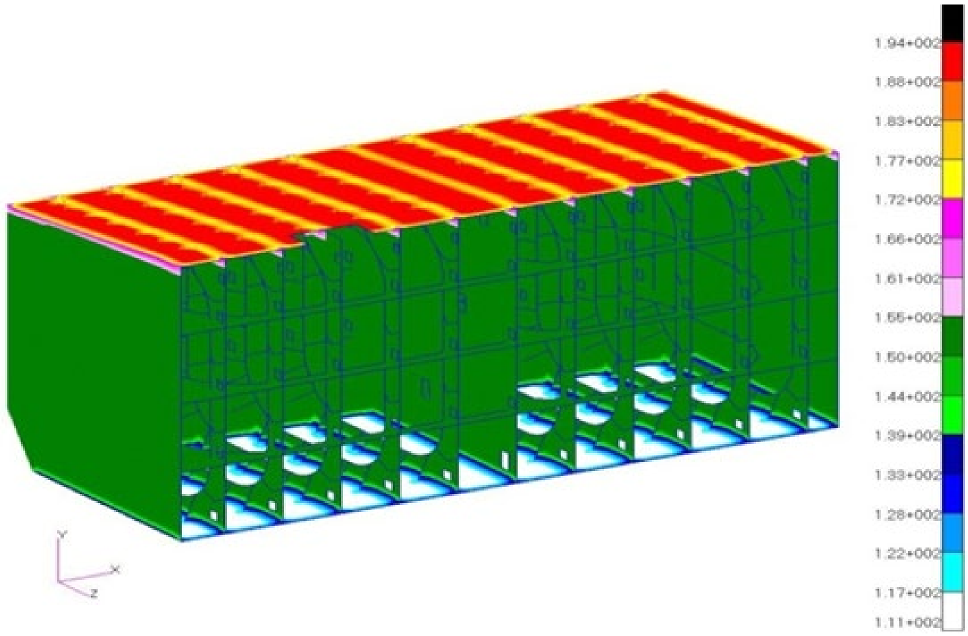
9.5 Full Loading Case

When the cargo tank is fully filled with liquefied gas, the temperature inside the cargo tank is assumed to be in a steady state and to remain constant at the cargo temperature.

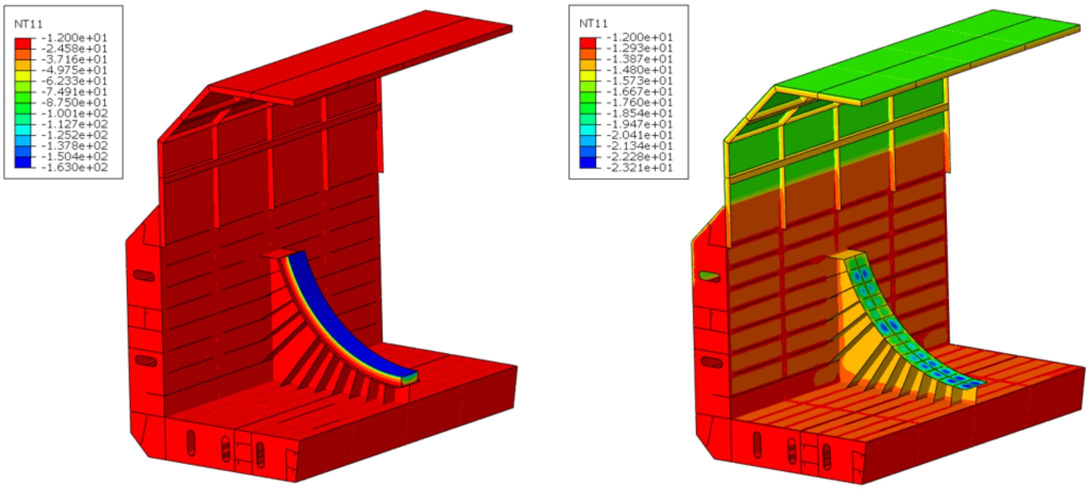
11 Temperature Distributions

The results from FE heat transfer analysis include nodal temperatures in the whole FE model. Section 3, Figure 4 shows examples of temperature distributions on an independent Type B LNG tank for cooling down condition and a Type C supporting structure for the contact of LNG tank, respectively. The FE results of temperature distributions can be used as loading conditions for the sequential thermal FE stress analysis of the tank structure.

FIGURE 4
Examples of Temperature Distributions



(A) Temperature Distribution of Independent Tank



(B) Temperature Distributions of a Supporting Structure with Press-wood (Left) and without Press-wood (Right)

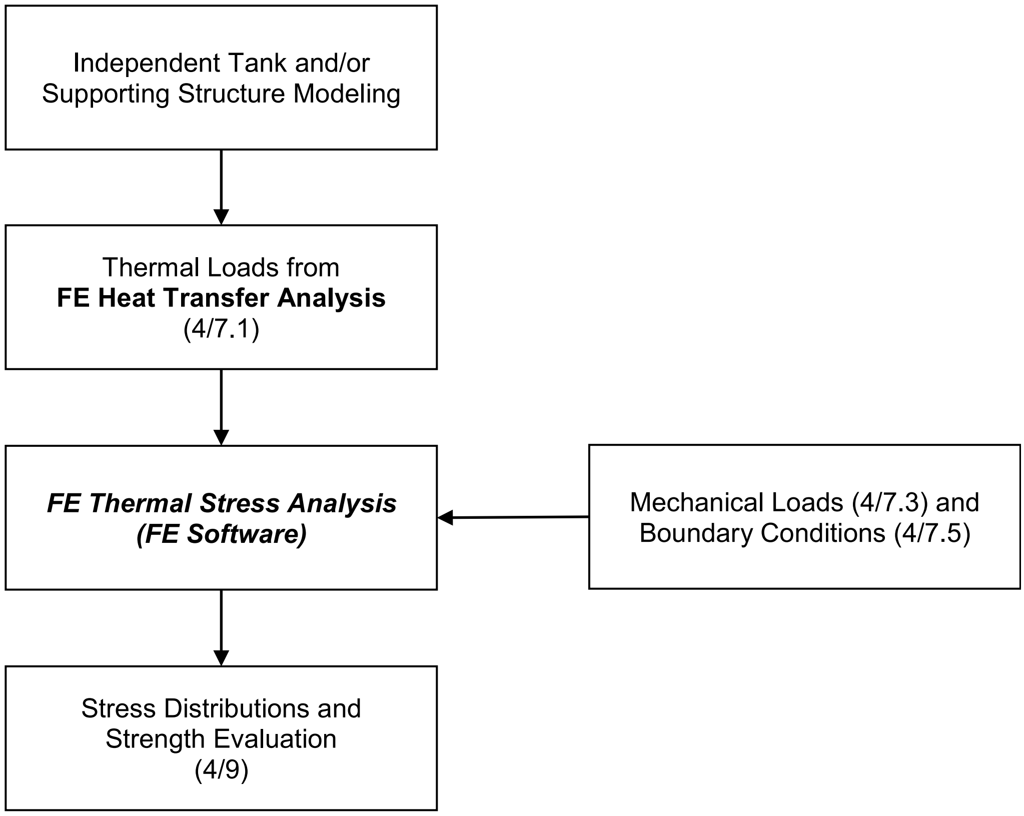
SECTION 4 FE Thermal Stress Analysis and Strength Evaluation

1 General

Thermal stress analysis is applied to independent-type tanks. For independent Type B prismatic tanks, high local stress concentrations may occur at welds around and adjacent to the connection among the tank wall and stringers/girders as well as stiffeners, due to the thermal gradient around the liquid line inside the tank. Thermal loads due to temperature gradients should be combined with mechanical loads such as internal pressure for FE thermal stress analysis and strength evaluation.

According to A5/9 of the *LGC Guide*, thermal stress analysis is required for independent Type B tank structure. The total stresses of the independent tank structure under different loading cases are obtained for structural strength evaluation. Each panel in the tank wall should be evaluated against yielding and buckling strength. For a vessel with independent Type C tank which is primarily constructed of bodies of revolution, thermal stress analysis should be performed on supporting structures. The detailed flowchart of FE thermal stress analysis and strength evaluation in these Guidance Notes is provided in Section 4, Figure 1.

FIGURE 1
Flowchart of FE Thermal Stress Analysis and Strength Evaluation

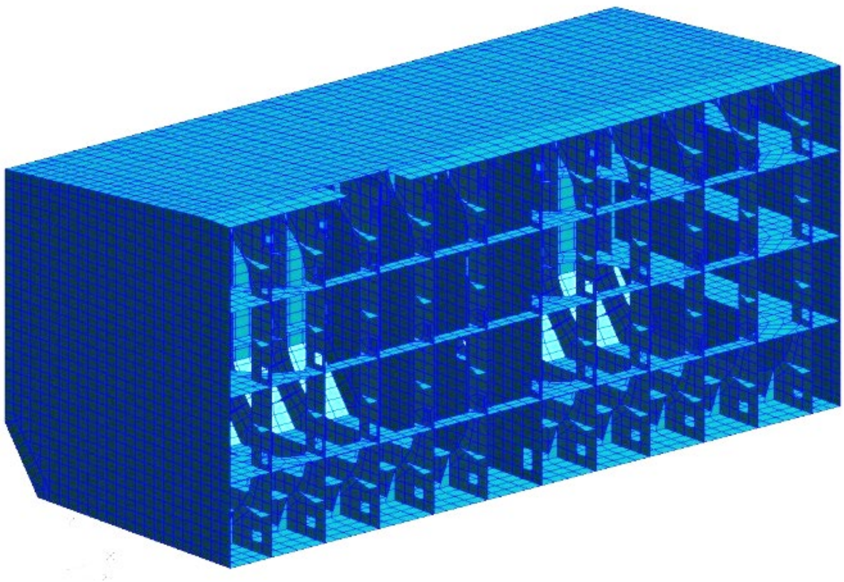


3 FE Model for Thermal Stress Analysis

The thermal contraction and expansion of an independent cargo tank caused by the loading of liquid cargo can produce local high stresses due to the geometric complexity of the structure. FE thermal stress analysis should be carried out to verify the structural integrity of a tank under thermal loads during the loading of liquid cargo or initial cooling-down period, as stated in Subsection 3/9.

The half tank structure should be considered in the FE model due to structural symmetry. For thermal stress analysis, shell elements are usually employed to model the tank skin and major plates, and beam elements are used to model local stiffeners, as illustrated for an independent Type B tank in Section 4, Figure 2. The beam elements need to be added back to the FE heat transfer model if needed, which does not accept beam elements for heat transfer analysis, to generate the FE model for thermal stress analysis. The FE mesh should be fine enough to capture local high stress concentration at critical areas near the welding connections. Preferably, shell elements should be used for stiffeners within the area of concern to replace beam elements in order to yield more accurate results.

FIGURE 2
FE Independent Tank Example



5 Material Properties

The following material properties need to be defined for FE thermal stress analysis: Young's modulus, Poison's ratio, mass density, thermal expansion coefficient, and reference temperature for thermal expansion coefficient. When applicable, the material properties should be selected in accordance with the corresponding service temperature.

7 Loads and Boundary Conditions

7.1 Thermal Loads

The temperature gradient of independent-type tanks, their associated substructure members, and/or supporting structure may introduce significant thermal strains and stresses. The field temperature distributions of the relevant areas obtained from the FE heat transfer analysis in Section 3 are imported or mapped to the FE thermal stress analysis model herein. The corresponding initial temperature for thermal stress analysis is specified in accordance with the operation conditions.

For independent-type tanks with internal stiffeners and stringers/girders that may cause high local thermal stresses, unfavorable temperature distributions due to different filling cases should be considered in accordance with Subsection 3/9.

7.3 Mechanical Loads

Mechanical loads such as design internal pressure for independent tank structural analysis should be considered to be applied to the tank structure in accordance with the filling cases in Subsection 3/9. In each partial filling case, the hydrostatic pressure due to the filled liquefied gas together with the design vapor pressure should be applied to the tank structure together with thermal loads. It should be noted that there is no hydrostatic cargo pressure in the cooling-down case.

7.5 Boundary Conditions

For an independent tank structure, rigid translations and rotations are usually constrained at selected nodes as boundary conditions.

For a Type B prismatic tank, the tank is supported by the hull in a manner which prevents bodily movement of the tank under static and dynamic loads while allowing contraction and expansion of the tanks under temperature variations and hull deflections without undue stressing of the tanks and of the hull. In general, the protruding part of a support (chock) is fitted to the cargo tank to prevent potential problems associated with undue tightness at the contact surfaces due to shrinkage of the cargo tank under low cargo temperature.

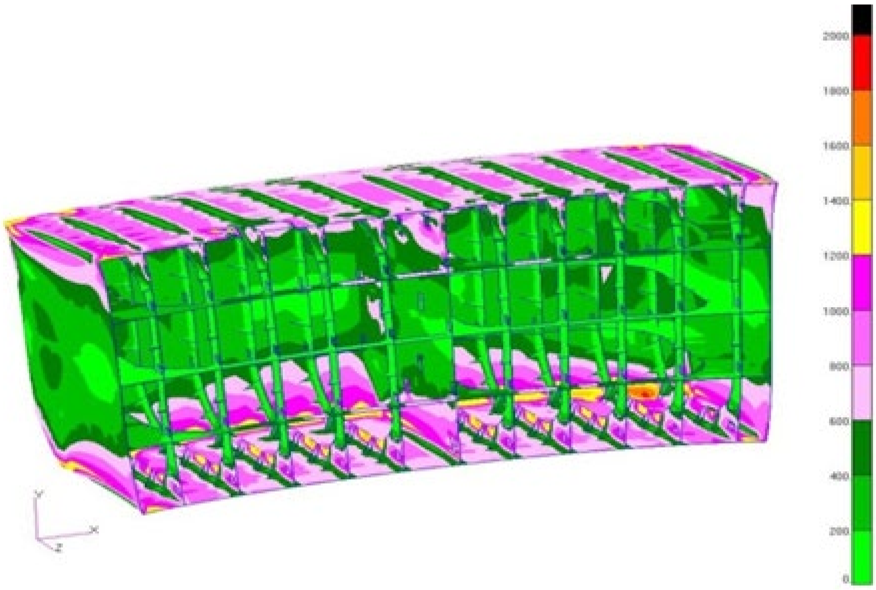
For a Type C tank, the tank is connected to the hull or deck by means of saddle supporting structures. In order to reduce high thermal stress caused by the thermal deformation that occurs during loading and unloading, one end saddle support is fixed while the other end is designed to slide freely longitudinally to compensate for the contraction and expansion caused by the temperature change.

9 Strength Evaluation

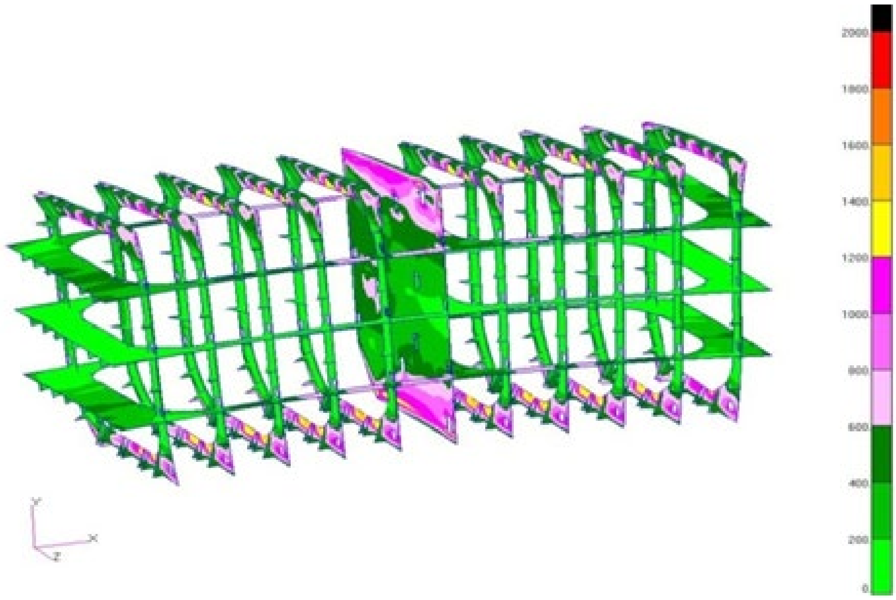
A global finite element model of a tank structure with proper boundary conditions should be used for FE thermal stress analysis. The thermal expansion coefficient for the tank material specified in Subsection 4/5 is employed in numerical modeling. Each thermal gradient specified in the loading cases in 4/7.1 together with other mechanical loads given in 4/7.3 should be applied to determine the total stress at critical locations of the tank structure. The FE stress results are used for the strength evaluation of the tank structure based on the design requirements in the IMO IGC code or ABS *LGC Guide*.

Section 4, Figure 3 gives an example of stress distributions of an independent Type B LNG tank under thermal and mechanical loads. The stress results are used to evaluate the structural adequacy of primary and secondary structural members such as the cargo tank bottom, side shell, deck, stringers, girders, transverse webs, longitudinal and transverse bulkheads, and stiffeners.

FIGURE 3
Example of Stress Distributions of Independent Tank



(A) Stress Distributions of Tank Plates and Major Stiffeners



(B) Stress Distributions of Internal Members

APPENDIX 1 References

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