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EXPERIMENTAL STUDY ON THE PERFORMANCE OF SHIP FIRE PROTECTION MATERIALS

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Key word: fire protection materials, heat insulation, sound absorption and insulation.

ABSTRACT

The performance of heat insulation, sound absorption and insulation of ship fire protection materials is experimentally investigated in this paper. The fire protection materials of rock wool 60 k (60 kg/m^3) and ceramic fiber 80k (80 kg/m^3) are tested to show the requisite minimum thickness for the regulation of IMO heat insulation A class. The results show that the heat insulation performance of ceramic fiber (25 mm) and rock wool (50 mm) meets the requirement of A-30 class bulkhead. However, the composition of ceramic fiber (25 mm) and rock wool (25 mm) with the ceramic fiber exposed to fire can satisfy the requirement of heat insulated A-60 class bulkhead. Both of the two materials with the thickness over 25 mm have the value of noise reduction coefficient (NRC) over 0.72. The steel panel, with the sound transmission class (STC) 45, dominates the sound insulation capability of a bulkhead assembled by the steel panel and fire protection materials.

INTRODUCTION

To consider the safety and comfort of the passenger and crew in ship, the performance of heat insulation, sound absorption and insulation of ship decorative materials is an important issue. Furthermore, it is obvious that the weight and volume of the ship decorative materials have the significant limitation for the practical requirement of ship capacity. Therefore one often tries to decorate the ship by using the fire protection materials with the integrated performance of heat insulation, sound absorption, and sound insulation.

Fire on ship can be caused by electrical faults, ignition of spilt hydraulic oil or petroleum and in warships by strikes from missiles and bombs. Fire may be communicated from one deck to another or from one compartment to another on the same deck, by heat conduction through a steel bulkhead or deck. The speed that a fire may develop in an adjacent compartment will be dependent on the heat insulation nature of the fire protection material which is in contract with the surface of the division of the existing fire. Furthermore, to ease the fire fighters to extinguish it, fire must be confined in the compartment of ignition and prevented it spread out to other zones. Therefore the heat insulation capability of fire protection material is one of the most important safety problems.

The SOLAS convention [10] and IMO resolution [9] had the regulation about the fire protection construction and materials for a new ship, and the fire resistance and heat insulation performance of any decorative materials has been the subject of numerous theoretical and experimental studies. Badaruzzaman *et al.*, [5] experimentally investigates the fire resistance performance of an innovative composite panel materials. Gibson & Hume [7] show the fire characteristics of composite laminates for marine and offshore structural application by using experimental and numerical methods. A fire resistance test of a material with high water content is conducted to obtain the test temperature response and water content of the test materials by Jin *et al.*, [12]. Hoyning and Taby [8] summarized the IMO requirements related to fire reaction and fire resistance for a composite vessel and discussed the relation between different structural materials and structural integrity during a fire. The result shows that composite structures can meet the new requirements with little or extra weight or cost, and that the total weight benefit over steel and aluminum can be maintained. The rate of temperature rise of both the steel and the insulation materials using Eurocode 3 Formulation was discussed by Wong and Ghojel [16].

Because of concern about the effect of noise on the comfort of passengers and crew, the performance of sound absorption and insulation of the fire protection materials is the requirement in the ship compartment. For effective noise reduction, the accurate determination of sound absorption and insulation characteristics of ship fire protection materials is as much important as

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noise measurements. The sound absorption coefficient is a measure of the effectiveness of materials as sound absorbers; it can be measured by impulse and impedance tubes techniques. In the impulse technique using the reverberation room, the repeatability of impulse is a problem and more over at high frequencies difficulty exists in producing sufficient energy. Therefore, another method, two microphone transfer function method, has been developed by using impedance tubes.

Cops *et al.*, [6] shows that a lot of changing parameters can cause considerable errors of measuring the sound absorption coefficient of materials in a reverberation room. Kruger and Quickert [14] developed a computer aided test method to measure the acoustic parameters of absorber specimens in impedance tubes. Sound transmission class (STC) is used to evaluate the performance of sound insulation of materials. The effect of material parameters such as mass/area, fiber type, crimp, and binding fiber content on the sound transmission loss of a lightweight wall system has been studied by Narang [15].

In this paper, the ceramic fiber 80k (80 kg/m^3) and rock wool 60k (60 kg/m^3) were chosen to be the test fire protection materials. The heat insulation tests on the fire protection materials fixed direct on a steel panel surface were conducted, and the minimum thickness of the materials to meet the requirement of A-60 class bulkhead was obtained. Their sound absorption coefficient and sound transmission loss were also investigated by using the impulse method and two microphone transfer function method.

MEASUREMENT OF SOUND ABSORPTION PERFORMANCE

The sound absorption coefficient, α, which is a function of the frequency, is defined as the fraction of the incident acoustic energy which is absorbed by a surface,

$$\alpha = \frac{I_i - I_r}{I_i} \tag{1}$$

Where I_i, I_r are the sound intensity of incident and reflected wave respectively. The absorption coefficient α can have a value between 0 and 1. The impulse and impedance tube techniques are two methods to measure the sound absorption coefficient. The noise reduction coefficient, NRC, is found by averaging the sound absorption coefficient at the frequencies 250, 500, 1000, and 2,000 Hz.

1. Technique of impulse

In the impulse method, random incidence is employed by placing the test sample in a large reverberation room wherein sound waves strike the large test sample from many directions simultaneously. A tone burst at the test audio frequency is generated in the reverberant room and is allowed to decay. The reverberation room is an oblique angled room with pairs of nonparallel walls to maximize sound field diffuseness as shown in Figure 1. The location of test absorbent, measure microphones, and loudspeaker is also arranged in this figure. The most important geometrical data of the reverberation room are: volume 202 m^3; total surface area 250 m^2. The measurements were performed following the ASTM C423 [2] and CNS 9056 prescriptions. Reverberation times have been done with loudspeaker in the 1/3 octave band centre frequency range from 125 Hz to 8000 Hz. The absorption material was placed on the floor with covering a single area as near as possible to 12 m^2 . The loudspeaker was positioned at one of the corners of the room and 1 m above the floor.

Since the rate of decay is dependent on the amount of absorption available, sound absorption coefficient of the test absorbent is calculated using the measured reverberation time and other parameters of the reverberation room. The reverberation time T_1 and T_2 are measured for the reverberation room without and with the absorbent materials individually, and the sound absorption coefficient can be found from,

$$\alpha = \frac{55.3V}{cS}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{2}$$

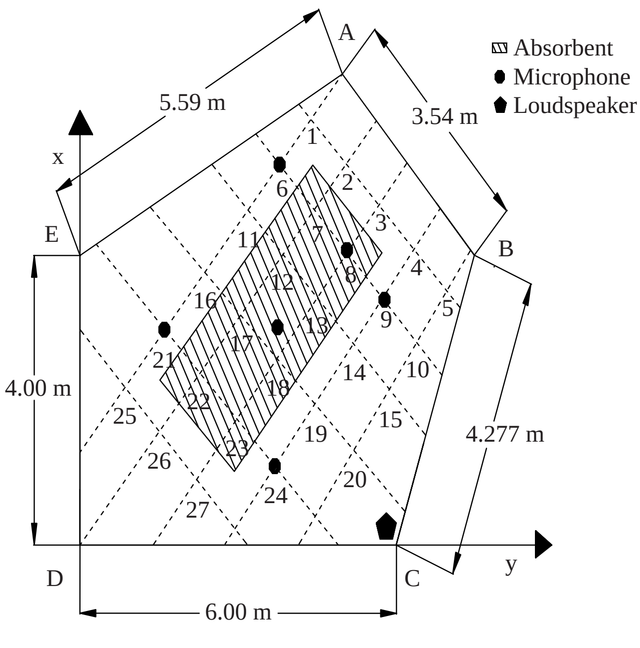

Fig. 1. The size and arrangement of the reverberation room for impulse technique.

Where S, V and c are the superficial area of absorbent material, reverberation room volume and sound speed individually.

2. Technique of impedance tubes

Impedance tubes technique measures the normal incidence sound absorption coefficient and surface impedance of absorbent material. This technique includes the standing wave ratio method and two microphone transfer function method. It is well known that the standing wave ratio method is time consuming and tube becomes too long at low frequencies due to discrete frequency excitation. The two microphone transfer function method is faster and convenient for measurements due to broad band excitation. Further, random and bias errors are significant reduced. Thus the two microphone transfer function method uses an impedance tubes to measure the sound absorption coefficient is performed in this paper. The microphones are firmly mounted on the tube. The microphone separation s should satisfy the condition:

$$s \leq 0.7\ (c/2f_{mc}) \tag{3}$$

Where f_{mc} is the maximum cut off frequency and defined by the relation:

$$f < 1.84(c/\pi D) \tag{4}$$

D is the tube diameter. Random signal is generated by a sound drive mounted on one side of the tube, at the other end is the circular test sample.

The two microphone transfer function method was made to follow ASTM E1050-98 [1] and ISO 10534-2 [11] by using the frequency analyzer OR25 to analyze the complex transfer function H_{12} between two separated microphones. The sound reflection coefficient R can be calculated from:

$$R = \frac{H_{12} - e^{-iks}}{e^{iks} - H_{12}} \cdot e^{i2kx_1} \tag{5}$$

Where $s = x_1 - x_2$ and x_1, x_2 are the position of two microphones. According to the measuring frequency range, the impedance tubes technique need two tubes with the same length L = 880 mm and different diameter D. The large tube with D = 100 mm, s = 85 mm and the small tube with D = 35 mm, s = 30 mm are for measuring the low and high frequency range sound reflection coefficient respectively. The sound absorption coefficient can be obtained from the definition:

$$\alpha = 1 - |R|^2 \tag{6}$$

MEASUREMENT OF SOUND INSULATION PERFORMANCE

This measurement consists of the use of a reverberation room and anechoic room which are separated by the test panel under investigated. Under sufficiently diffuse in reverberation room with volume V, the sound power incidence from the test panel area A can be written by using the source power E:

$$W_{inc} = EcA/4V \tag{7}$$

The sound intensity method, following the standards of ASTM E90-04 [3] and E413-04 [4], is used to measure the sound intensity I_i at the N measurement unit area A_i in the anechoic room, and the sound power transmission from the test panel can be calculated as:

$$W_{trans} = \int_A \boldsymbol{I} \cdot d\boldsymbol{A} = \sum_{i=1}^{N} I_i A_i \tag{8}$$

By using the definition of transmission loss [13]:

$$TL = 10 \cdot \log_{10} \frac{W_{inc}}{W_{trans}} \tag{9}$$

The transmission loss can be written as:

$$TL = Lp + 10 \cdot \log_{10} A + 10 \cdot \log_{10} \frac{100}{\rho C} - 10 \cdot \log_{10} \left(\sum_{i=1}^{N} 10^{\frac{L_{Ii}}{10}} A_i \right) \tag{10}$$

Where the L_p is incident average sound pressure level and ρ is air density. The sound transmission class, STC, presented by a reference contour provides a single number specification of acoustic isolation characteristics of a panel. A reference contour consists of three segmental straight lines: a low frequency segment that increases by 15 dB from 125 to 400 Hz, a middle segment that increases by 5 dB from 400 to 1250 Hz, and a horizontal segment at high frequencies. As shown in Figure 8 to Figure 10, the curve with triangular marks and consisting of three different slope segments is the reference contour. The reference contour is selected to compare with the measurement values of transmission loss so that the maximum deviation of the data below the contour at any one frequency does not exceed 8 dB and the total deviation of the data below the contour at all frequencies does not exceed 32 dB.

HEAT INSULATION TEST

1. Furnace structure and temperature control

The multi-function furnace with the body size

1500 mm in length, 1500 mm in width, and 1800 mm in depth is used to investigate the heat insulation performance of fire protection materials of ship bulkhead. The walls of the furnace inside, lining with 200 mm thickness ceramic block to resist heat to high temperature up 1260°C, are constructed with 3.2 mm thickness plate steel to increase its strength. The temperature in the furnace is adjusted by the temperature automatic control devices to meet the requirement of IMO temperature rising curve in Figure 2; the temperature automatic control devices include 60 Hz AC110V/220V DCP-216 Honeywell 19 Pattern temperature control program, SDS-200 Honeywell temperature regulator, automatic gas ignition button, and safety alarm system.

The temperature in the furnace is measured by six *k*-type thermocouples which impenetrate into the inside of furnace and transmitted to Yokogawa hybrid recorder DR230 by thermocouple compensation wire. To control motor and adjust the fuel to air ratio valve, the temperature data is also transfer to temperature control program for comparing with the pre-setting temperature. Therefore the furnace temperature rises can be continuously controlled to follow the standard time-temperature curve within the limits. It is defined that during the first 10 min of the test area under the mean furnace temperature curve should not vary by more than ±15% of the area under the standard curve.

As shown in Figure 2, the test samples at the furnace front inside were exposed to heat environment which was heated with controlled fuel input to meet the following standard temperatures measured above the initial furnace temperature [9]. In Figure 2, the furnace inside average temperature rising curve coincides with these standard temperatures at the points with ■ mark.

At the end of the first 5 min 556°C
At the end of the first 10 min 659°C
At the end of the first 15 min 718°C
At the end of the first 30 min 821°C
At the end of the first 60 min 925°C

2. The size of test specimen

The size of the steel structural core recommended by the IMO resolution A.157 (13) is 2400 mm × 1910 mm × 4.5 mm. However, due to smaller scale furnace available only, the fire test steel structural core of dimension 1500 mm × 1500 mm × 4.5 mm was used instead. As shown in Figure 3, the vertical stiffeners of dimension 65 mm × 65 mm × 6 mm and spacing 500 mm were also used to increase the strength of steel structural core. A fire protection material used to insulate the structural core of a test specimen for A-class bulkhead insulation is tested in the vertical position in a similar manner as the bulkhead panel and without paint or other superimposed finish. In Figure 3 the o and × indicate positions of surface thermocouples; thermocouples marked × are only required to be fitted to a specimen of an A-class heat insulation test.

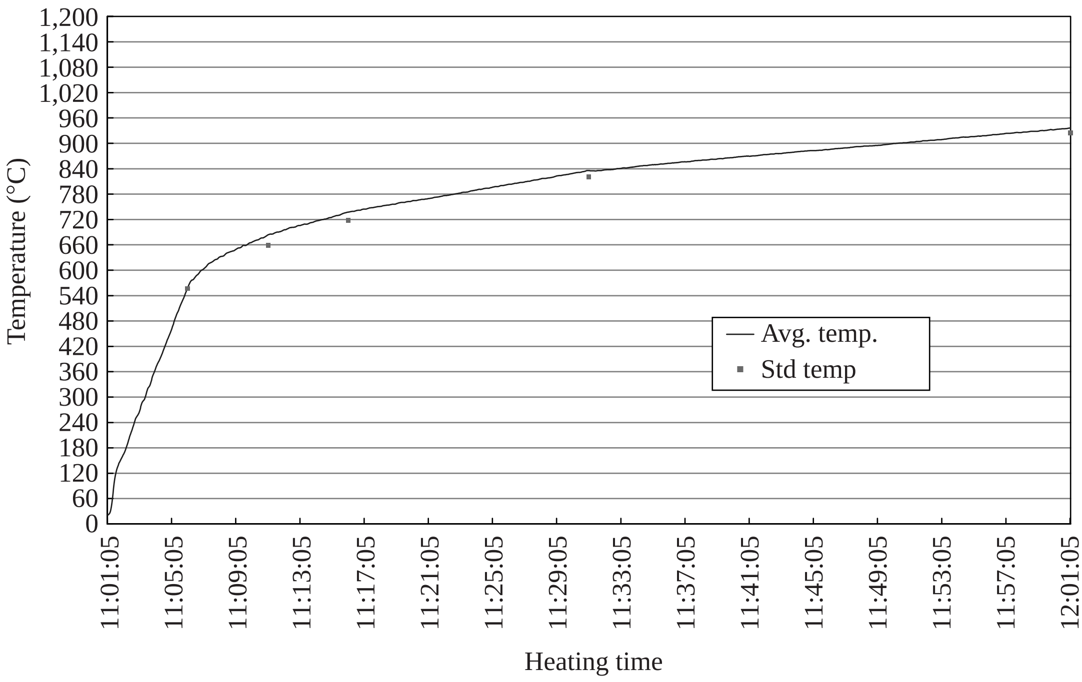

Fig. 2. The inside furnace heating temperature curve following the requirement of IMO standard temperature rising.

3. The insulation requirements

Thermal insulation requirements of the specimen should be such that the average temperature reading of the thermocouples on the unexposed surface will not rise more than 139°C above the initial temperature, nor will the temperature at any one point on the surface rise more than 180°C above the initial temperature [8]. If A class divisions are to be A-60, A-30, A-15 or A-0 standards, the above temperature limits should not exceeded during the time 60 min, 30 min, 15 min or 0 min individually.

4. The selection of test samples

Heat insulation tests for fire protection materials of ship were performed using a steel panel combine with the fire protection materials. It is well known in the literature that the ceramic fiber and rock wool, noncombustible materials, have good fire resistance and light weight characteristics. Thus, in this study, these materials were selected for investigating the minimum thickness to meet the insulating class. The sound absorption and insulation performance of these materials are also investigated to provide the ship designer.

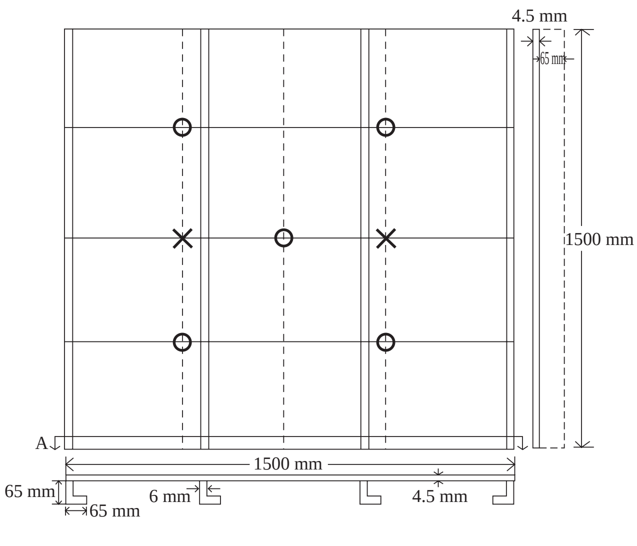

Fig. 3. Heat insulation test specimen for A class bulkhead.

RESULTS AND DISCUSSION

The results of experimental investigations for the performance of ship fire protection materials will be presented. The performance of sound absorption and insulation of the fire protection materials was first measured in the laboratory of the department of system engineering and naval architecture of National Taiwan Ocean University. Then the same materials were used to investigate their performance of heat insulation in the fire prevention center of National Cheng Kung University. In these investigations, to consider the limitation of ship weight and space, the fire protection materials were fixed to contact on the surface of steel panel directly. Two popular fire protection materials, ceramic fiber (80 k) and rock wool (60 k), with the performance of low density and fire resistance, were chosen in this investigation. The physical properties of the steel panel, ceramic fiber, and rock wool were tabulated in Table 1.

1. Sound absorption coefficient measurement

A fire protection material direct fixed on the surface of steel panel with the higher value of sound absorption coefficient will have the better performance of sound absorption. The sound absorption coefficient of ceramic fiber (80 k) with thickness 25 mm and rock wool (60 k) with thickness 50 mm is measured by using reverberation room and impedance tubes. Figures 4 and 5 show the sound absorption coefficient at 1/3 octave band center frequency of rock wool by the method of using reverberation room and impedance tubes respectively. The value of NRC = 0.77 and NRC = 0.71 is calculated from the Figures 4 and 5 individually. Therefore, the coefficient value measuring from the reverberation room will have a little higher than that from the impedance tubes. The results of the same investigation for ceramic fiber are shown in Figures 6 and 7; the NRC = 0.72 and NRC = 0.64 are obtained from Figsures 6 and 7. Compare with Figsures 4 and 6 or Figures 5 and 7, it can be found that the sound absorption coefficient of rock wool higher than that of ceramic fiber. The result is due to the former with double thickness compare to the latter.

Table 1. The physical properties of steel and fire protection materials

	Steel	Ceramic fiber	Rock wool
Density (kg/m^3)	7850	80	60
Thermal conductivity (W/m°C)	52	0.047	Under 0.047
Melting point (°C)	Over 1500	Over 1200	Under 650

2. Sound insulation measurement

A specimen with the higher value of sound transmission loss will have the better performance of sound insulation. The test steel panel with dimensions of 1240 mm (high), 1485 mm (width) and 4.5 mm (thickness) was vertically mounted between the reverberation room and anechoic room in this measurement. Three specimens, steel panel, rock wool fixed on one side of the steel panel, and ceramic fiber fixed on one side of the steel panel, are performed to investigate the performance of sound insulation. To determine the STC of a specimen, its transmission loss is measured in the 16 contiguous 1/3 octave bands between 125 to 4000 Hz. Figure 8 show the sound transmission loss at 1/3 octave band center frequency of steel panel. The STC of the panel is then the value of the transmission loss corresponding to the intersection of the chosen reference contour with the 500 Hz ordinate, and it is equivalent to STC = 45. The sound transmission loss for rock wool and ceramic fiber fixed on the surface of the steel panel is shown in the Figures 9 and 10 respectively; the STC value of the former is 49 and the latter, 47. Based on the observation from Figures 8 to 10, it can be stated that the absolute majority of sound insulation of ship bulkhead or deck results from the steel panel which has high

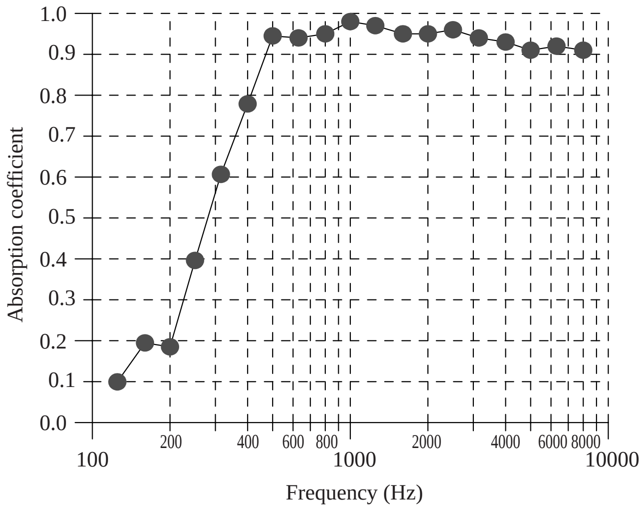

Fig. 4. The sound absorption coefficient at 1/3 octave band center frequency of rock wool 60 k by using the reverberation room.

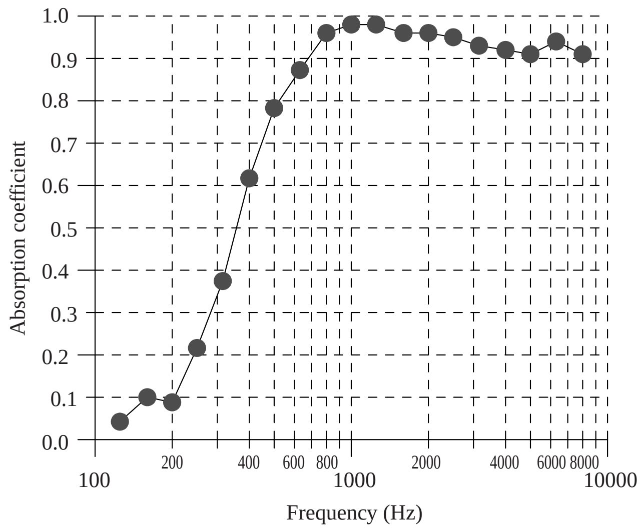

Fig. 6. The sound absorption coefficient at 1/3 octave band center frequency of ceramic fiber 80 k by using the reverberation room.

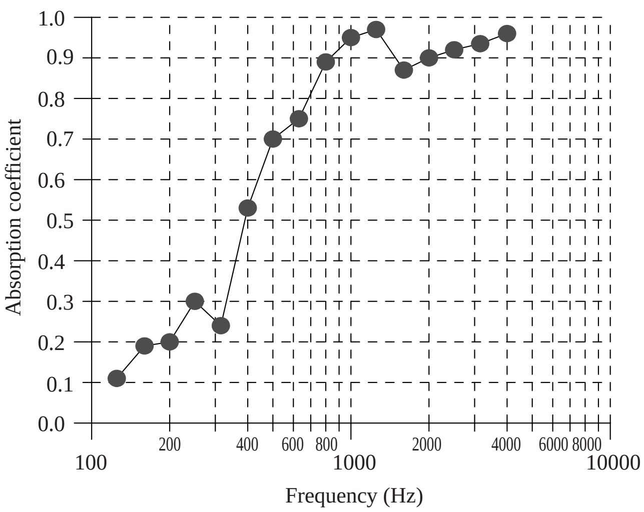

Fig. 5. The sound absorption coefficient at 1/3 octave band center frequency of rock wool 60 k by using the impedance tubes.

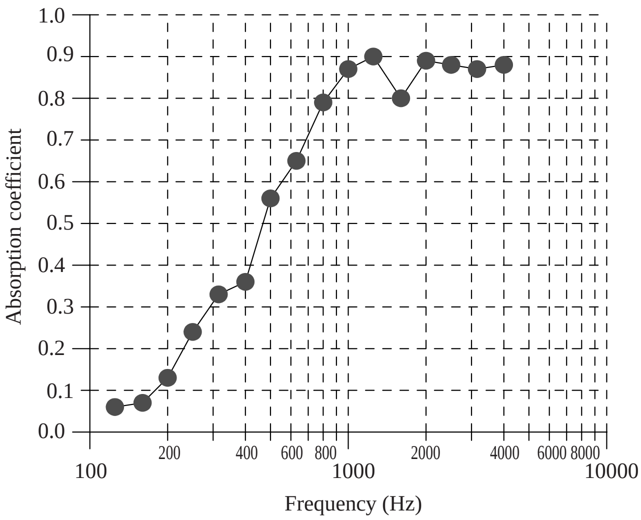

Fig. 7. The sound absorption coefficient at 1/3 octave band center frequency of ceramic fiber 80 k by using the impedance tubes.

density and rigidity.

3. Heat insulation test

The three different composite samples were tested and the fire protection materials were exposed to fire, as given in Figure 11. The sample size as described above is 1500 mm × 1500 mm. The temperatures of unexposed steel surface were recorded through nine thermocouples glued at selected positions on the front side surface of the test panel. However, according to the regulation, only the record temperatures of seven positions are considered to evaluate the heat insulating performance, as shown in Figure 3. Thermocouple-5 was fixed at the centre, while thermocouple-1 to thermocouple-3 were fixed from the higher marked position to lower marked position along the right side vertical line. The same arrangement for thermocouple-7 to thermocouple-9 was fixed along the lift side vertical line, as shown in Figure 3.

The 80 k ceramic fiber with thickness 25 mm fixed on the steel panel is the first sample. After the 60 minutes heat insulation test, the result of first sample shows that the exposed fire surface of ceramic fiber is no damage, as shown in Figure 12. However, the sample heated to 35 minutes and 44 seconds, the average temperature of seven positions rises more than 139°C above their initial temperatures. This result is clearly given in

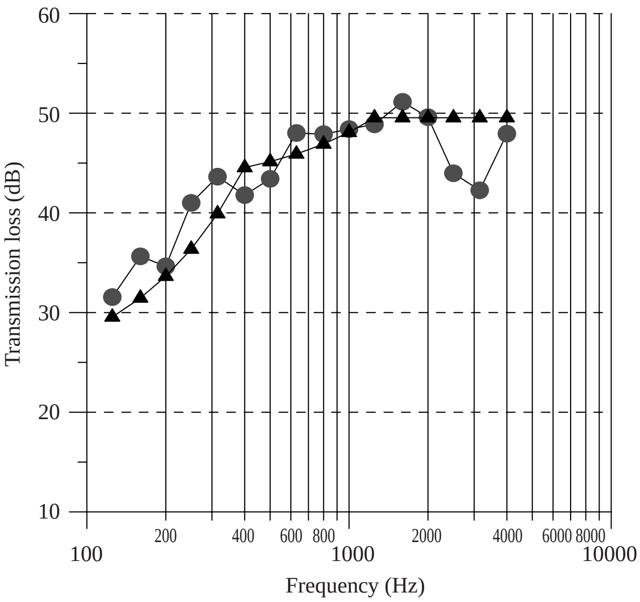

Fig. 8. The sound transmission loss at 1/3 octave band center frequency of steel panel.

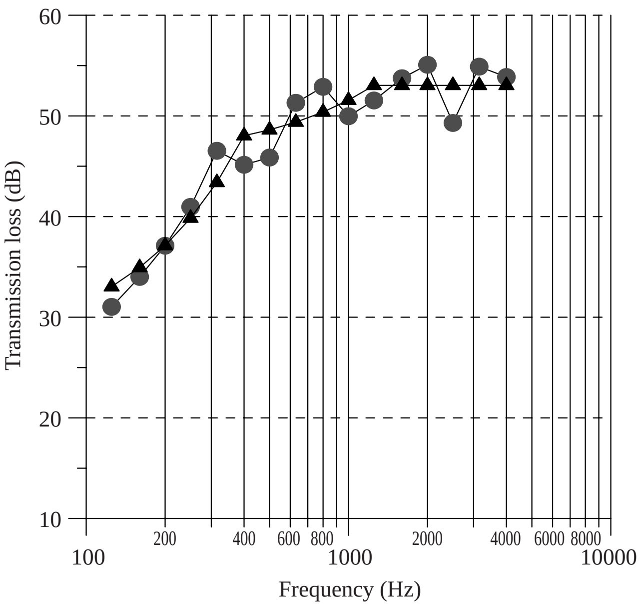

Fig. 9. The sound transmission loss at 1/3 octave band center frequency of rock wool fixed on the steel panel.

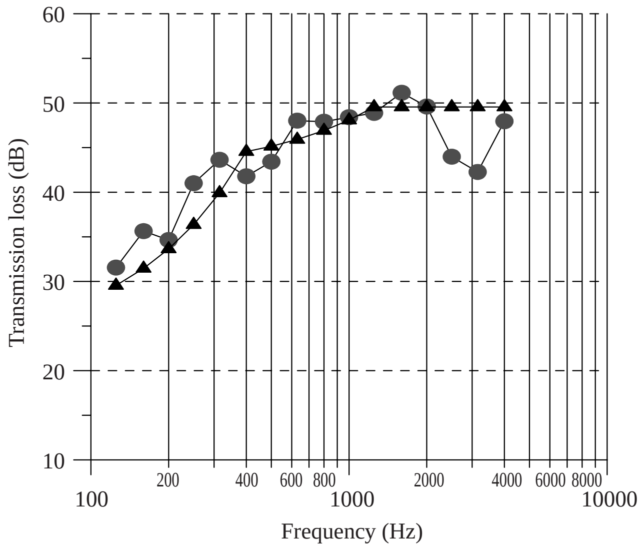

Fig. 10. The sound transmission loss at 1/3 octave band center frequency of ceramic fiber fixed on the steel panel.

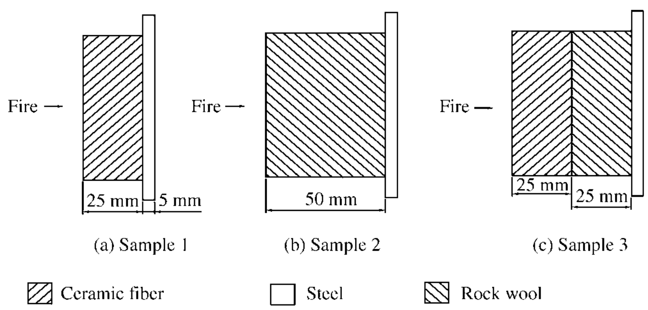

Fig. 11. The composition of three samples.

Figure13, in which the curve with rectangular mark ◆ over the red horizontal line. Alternately, the temperature of thermocouple-5 rises more than 180°C above its initial temperature when the sample is heated to 45 minute and 53 seconds. These results reveal that the 80k ceramic fiber with thickness 25 mm, used as a fire protection material of ship bulkhead, has A-30 class heat insulation performance.

Fig. 12. No damage surface of ceramic fiber after the 60 minutes fire test.

The second sample, 60 k rock wool with 50 mm thickness, is tested in the same installation and procedure as mention in the first sample. A photograph of this test material shown the surface melted damage after the 60 minutes heat insulation test is presented in Figure 14. The damage consisted primarily of degradation and charring of the rock wool surface due to melt and cracking within the melting portion of the fire protection material. The dark areas on the picture are the residual carbonaceous char of the melted surface of the rock wool. The light areas, unmelted portion under the residual carbonaceous char, result from the exfoliation of the residual carbonaceous char. This phenomenon reduces the heat insulation performance of the test material. Therefore, the average temperature of seven positions rises more than 139°C above their initial temperatures heated to 55 minutes and 45 seconds. As shown in Figure 13 the curve with triangular mark ▲ increases its slope and over the red horizontal line before the end of fire test. Though the thickness of the rock wool is double over that of ceramic fiber, the 60 k rock wool for a fire protection material of ship bulkhead due to lower melting point, as shown in Table 1, also only has A-30 class heat insulation performance. From these results, it can be concluded that the heat insulation characteristic of ceramic fiber (80 k) is superior to that of the rock wool (60 k).

To prevent the rock wool exposed to fire and melted to reduce heat insulation, the third test material

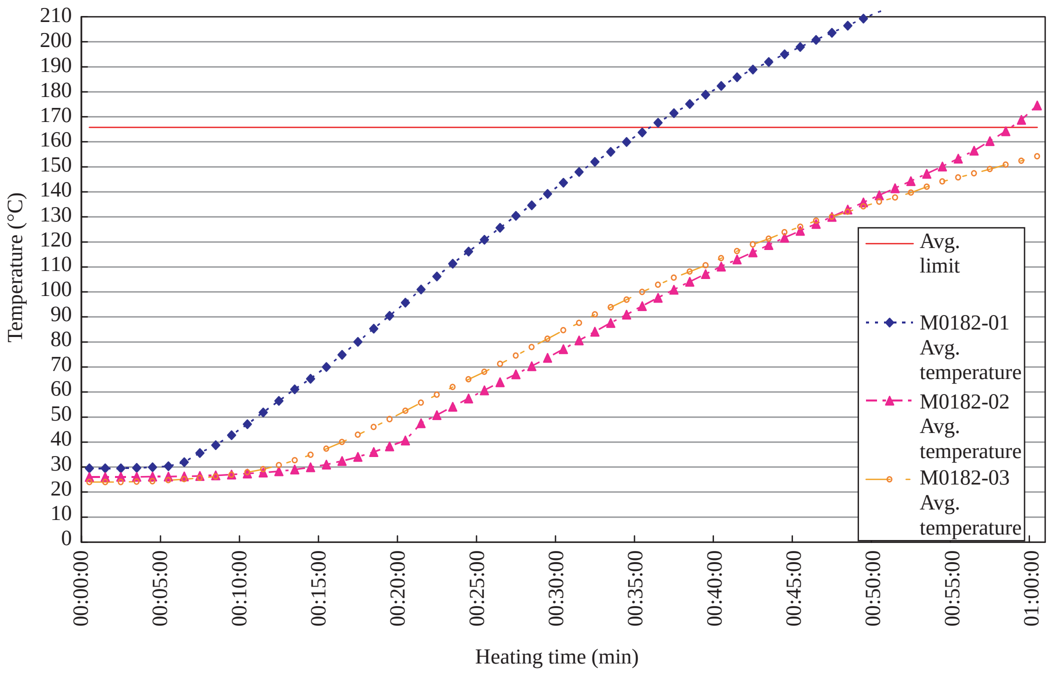

Fig. 13. The average temperature curve of seven points on the unexposed fire side surface of the test steel panel.

is composed of 80k ceramic fiber 25 mm thickness and 60 k rock wool 25 mm thickness. The rock wool is installed between the ceramic fiber and steel panel, and the ceramic fiber is exposed to the fire. The total 50 mm thickness of entire combine sample is no damage after 60 minutes fire test. The curve with circular mark ◯ in Figure 13 shows that the average temperature of seven positions rises above their initial temperatures not over 139°C until heated to 60 minutes. In Figure 15 the nine

Fig. 14. The melted damage of rock wool surface after the 60 minutes fire test.

temperature curves of the nine thermocouples do not rise over the higher red horizontal line. That is to say, there is no thermocouple with the temperature rise more than 180°C above its initial temperature. According to the previous results, the conclusion can be drawn that the total 50 mm thickness sample, combination of 80 k ceramic fiber and 60 k rock wool with the same thickness 25 mm, has A-60 class heat insulation capability. Therefore this combinative sample can be the fire protection material of ship bulkhead with minimum thickness and weight and having A-60 heat insulation performance.

CONCLUSION

Upon consideration of the limitation of ship weight and space, it can be stated that the low density ceramic fiber and rock wool are the first choice for ship fire protection materials. The heat insulation test and sound absorption and insulation measurement for these two fire protection materials are performed in this paper. Several conclusions can be drawn as follows:

1. The heat insulation capability of ceramic fiber 80 k with thickness 25 mm has the class A-30; it has the class A-60 heat insulation performance for this fire protection material with 50 mm thickness.
2. Due to low melting point and resulting surface carbonaceous char after fire test, the rock wool 60 k with thickness 50 mm can only satisfy the heat insulation class A-30.

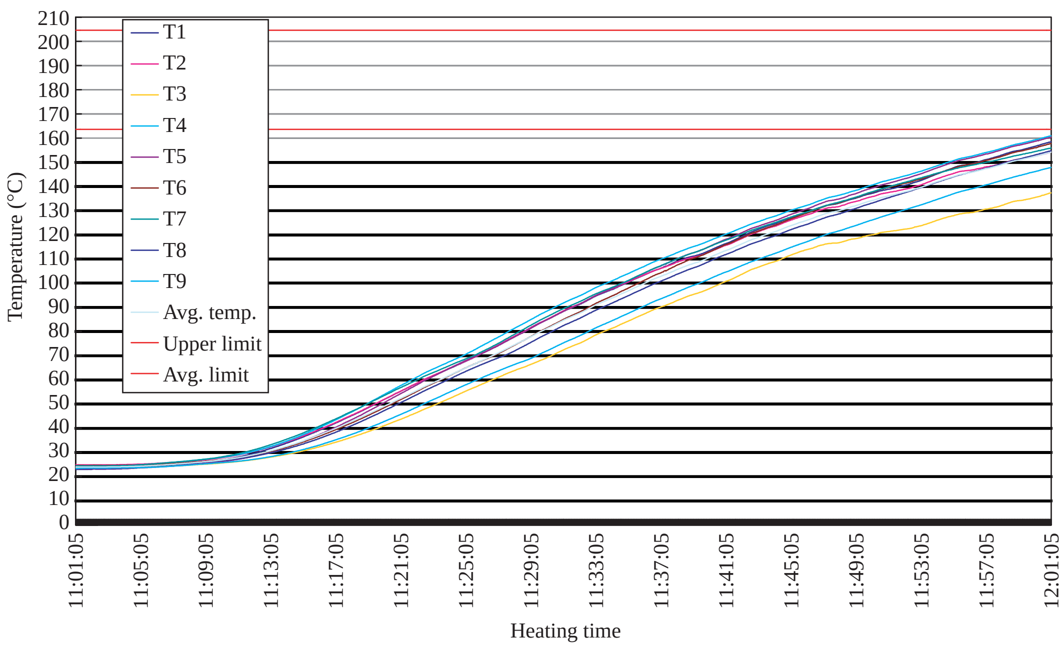

Fig. 15. The temperature curves of nine points on the unexposed fire side surface of the test steel panel.

3. The material, composition of 25 mm thickness ceramic fiber (80 k) and 25 mm thickness rock wool (60 k), has the heat insulation class A-60 under the condition of ceramic fiber exposed to fire.
4. The sound absorption capability of rock wool 60k with thickness 50 mm is better than that of ceramic fiber 80k with thickness 25 mm.
5. The sound transmission loss of steel panel with fire protection material results primarily from the steel panel.
6. The sound absorption coefficient of a material measured by using reverberation room is a little bit higher than that from using impedance tubes.

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