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The analysis of research results concerning heat release rates of ship materials with regard to dynamic parameters of the research station

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ABSTRACT

Based on the results of author's research it was stated that significant differences between heat release rates measured according to ISO 5660-1 and FTP Code Part 5 (Res. A. 653 (16)) are not caused by measurement uncertainties. A basic factor determining the lack of correlation is treating the heat release rate in the category of static measurements in the normalized measurement methods. Taking into account dynamic parameters of the test station allowed the coincidence rate (reproducibility and correlation) of the results of heat release rates measured using different methods to be improved, without changing test stations and procedures. Author's research performed on 42 materials has revealed that the relative dynamic errors of the heat release rate measurements are significant (2%÷120%). The average value of these changes for the tested group of materials was equal to 39%.

Keywords: fire safety, heat release rate, dynamic measurement

INTRODUCTION

Object safety evaluations aim at predicting and preventing possible hazards as early as at the planning stage of object operation. For this purpose databases are created on these hazards, their possible effects, frequencies of their appearance, along with protective measures applied and their efficiency. An object safety evaluation is expected to provide an exhaustive description of the object environment, its complexity and possible changes resulting from the hazard. In particular, evaluating fire safety on marine objects requires the information on heat release rates characteristic for thermal decomposition and combustion of materials. The heat release rate contributes to the rate of fire temperature changes, and to the emission of smoke and toxic products of thermal decomposition and combustion. Fire progress on a ship can be only controlled in the pre-ignition phase [1], when the heat release rate of burning materials does not exceed a critical value. The information on the heat release rate of the materials used in marine object cabins makes it possible to predict the fire progress and, consequently, to take appropriate actions and technical measures in order to evacuate people from the dangerous area and fight the fire during its initial phase.

RESEARCH

Numerous research methods oriented on evaluating heat release rates during thermal decomposition and combustion of materials have been developed. In the shipbuilding industry the heat release rates are determined using the methods defined in the FTP Code Part 5 [Res. A. 653 (16)] [2] and ISO 5660-1 standard [3].

The analyses of heat release rate tests found in the literature [4÷7], along with those done by the author using various methods have revealed no correlation between the obtained results (fig. 1).

Based on the analysis of author's results [8] it was concluded that significant differences between the heat release rates measured according to ISO 5660-1 and FTP Code Part 5 (Res. A. 653 (16)) are not caused by measurement uncertainties.

A decisive factor for the lack of correlation is treating the heat release rate in category of static measurements in the normalized measurement methods.

The basis for making distinction between static and dynamic measurements is the time variation of the measured quantity. Combustion of materials is a process that changes in time. That is why the measurement of the heat release rate should be treated as a dynamic process.

Consequently, the results of dynamic measurements are presented as time functions. Correctness of the presentation depends on factors both related and not to the variations of the measured quantity.

The pulse response functions of all transducers [9], except those of integral type, approach zero when $t \to \infty$ (fig.3).

Time characteristics of a transducer, given in the form of a pulse response k(t), make it possible to calculate the transducer response for any input signal x(t). Here the **Duhamel** integral is used [9].

$$y(t)=\int_0^t k(t-\tau)\cdot x(t)\cdot d\tau \qquad (1)$$

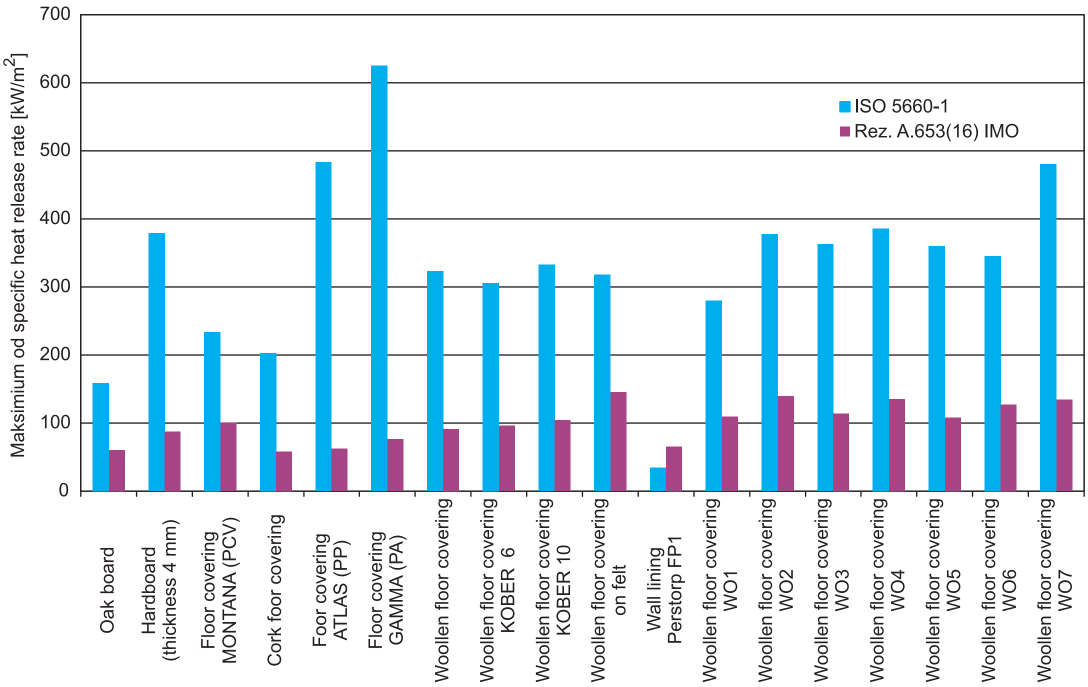

Fig. 1. *Comparison between maximum heat release rates defined using FTP Code Part 5 (Res. A. 653 (16)) and ISO 5660-1 standard, for heat stream rates on sample surface equal to 50 kW ×m^{-2} (author's results related to unit of surface area)*

Fig. 2. *Heat release rates obtained for wool carpet using ISO 5660-1 and FTP Code Part 5 (Res. A. 653 (16)) methods, and taking into account measurement uncertainties (k·u$_c$ – extended uncertainty)*

It can be assumed in practice that k(t) values can be neglected after a finite time period t_o (fig. 3). At any time t_i, the output value y(t) is equal to the integral of a product of a "reversed" characteristic with the starting point shifted to t_i and the input signal x(t).

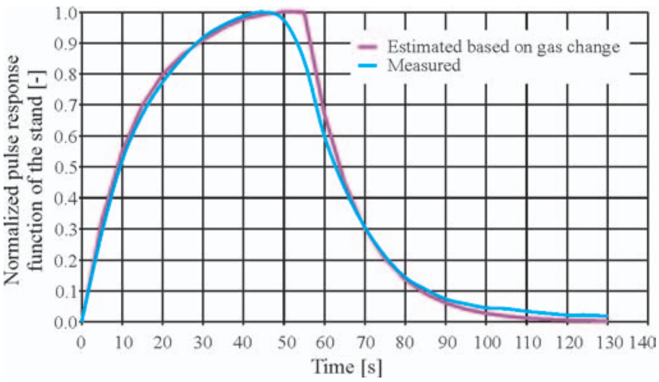

Fig. 3. *Normalized pulse response function of the stand, according to ISO 5660-1*

The above integral is represented by the area marked blue in fig. 4. which is proportional to the value of transducer response at t_i = 215 s. By "shifting" the pulse response function k(t-τ) along the time axis and performing relevant calculations (fig. 5) we can obtain the values of the transducer response y(t) at any time t.

It is clearly visible from figure 4 that the integral has nonzero values only for the time period ranging from t_i - t_o to t_i. Calculating the time-history y(t) can be interpreted as "shifting" the function k(t) along the time axis and performing the operations presented in the figure. Higher t_o values mean greater influence of the time-distant past input signal fragments on the current value of the transducer output. Therefore the pulse response function can be treated as a function which generates the output signal from the past input values. In case of slowly fluctuating signals any measuring transducer usually reacts as a delay transducer. When the rate of input signal variations increases - the input signal delay is observed at the beginning; further increase of the variation rate leads to signal distortion.

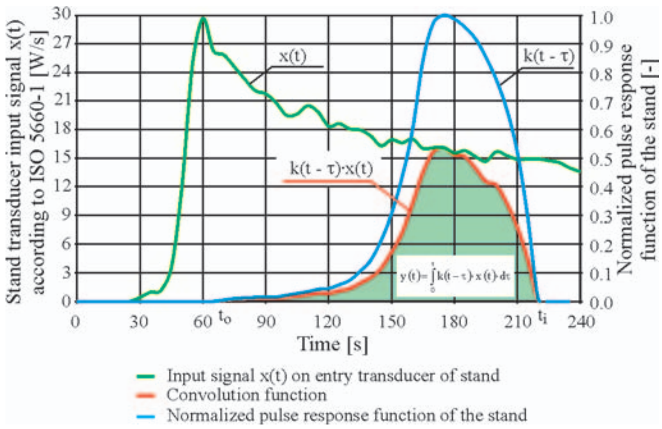

Fig. 4. *Interpretation of the transducer response calculation procedure making use of a convolution function*

To perform calculations the knowledge of the function x(t) is required, which minimizes practical use of those formulas.

The performed identification of the research stations as converters for heat release rate measurements consisted in determining the structure and functional relations that describe dynamic features of their measurement systems. Based on this identification it was determined that [8]:

- the station for testing the heat release rate using ISO 5660 method is a first-order converter with time constant T

- the station for measuring the heat release rate using FTP Code Part 5 (Res. A.653(16)) is a second-order converter described by: time constants T_1 and T_2, suppression factor ζ, and free vibration pulsation ω_o.

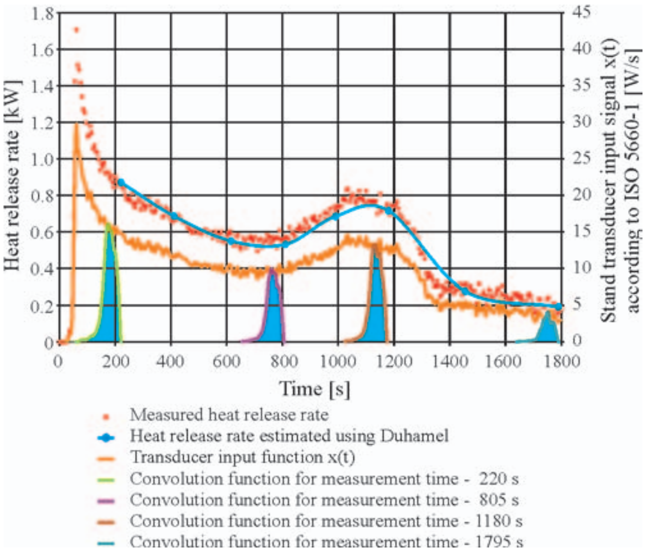

Fig. 5. *Interpretation of transducer response at different times using a convolution function*

Responses of the heat release rate test stations to linearly increasing inputs were used to correct the dynamic error. It was assumed (Fig. 6 and 7), that within the time interval: $t_i - \Delta t < t_i < t_i + \Delta t$ (where Δt is the measurement period) the measured heat release rate is a linear function with constant speed of changes a_i. The corrected heat release rate for the station making use of the method ISO 5660-1 was defined by the author as:

$$\dot{q}_k(t_i) = \dot{q}(t_i) + a_i T = \dot{q}(t_i) + \frac{\dot{q}(t_{i+1}) - \dot{q}(t_{i-1})}{t_{i+1} - t_{i-1}} T \quad (2)$$

The corrected heat release rate for the station using the FTP Code Part 5 (Res. A.653(16)) method is defined as:

$$\dot{q}_k(t_i) = \dot{q}(t_i) + a_i \frac{2 \cdot \zeta}{\omega_o} = \dot{q}(t_i) + \frac{\dot{q}(t_{i+1}) - \dot{q}(t_{i-1})}{t_{i+1} - t_{i-1}} \frac{2 \cdot \zeta}{\omega_o} \quad (3)$$

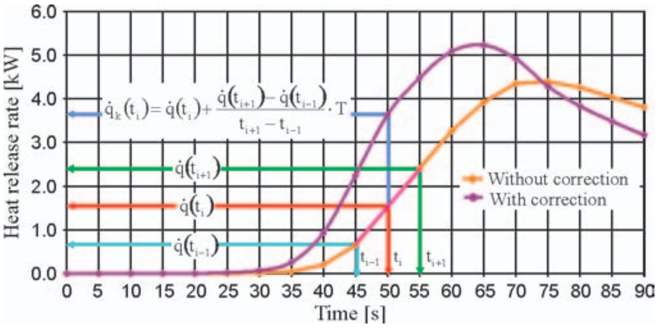

Fig. 6. *Principle of determining dynamic correction for heat release rate measurements making use of ISO 5660-1 standard*

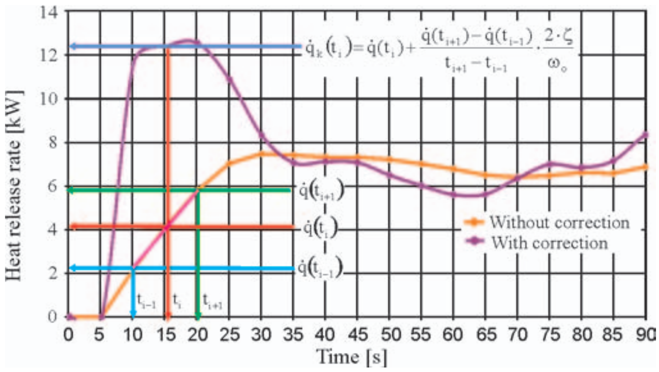

Fig. 7. *Principle of determining dynamic correction for heat release rate measurements making use of FTP Code Part 5 (Res. A.653(16))*

It is noteworthy that the dynamic error correction for the second-order converter does not depend on time constants T_1 and T_2 (3).

The validation of the dynamic error correction method has confirmed the agreement between the average values of the heat release rate obtained using the FTP Code Part 5 (Res. A.653(16)) and ISO 5660-1 methods.

Taking into account dynamic parameters of the heat release rate test station (Fig. 8) provided opportunities for increasing the coincidence rate (reproducibility and correlation) of the heat release rate results measured using different methods, without changing test stations and procedures.

The effect of the of dynamic error correction on the measured maximum of the heat release rate and on the heat released during material tests performed according to the FTP Code Part 5 (Res. A.653(16)) method is shown in Figs 9, 10, 11, 12 and 13.

As can be seen, the dynamic error of the heat release rate increases in those tests with the increase of the measured value of the heat release rate (Fig. 9).

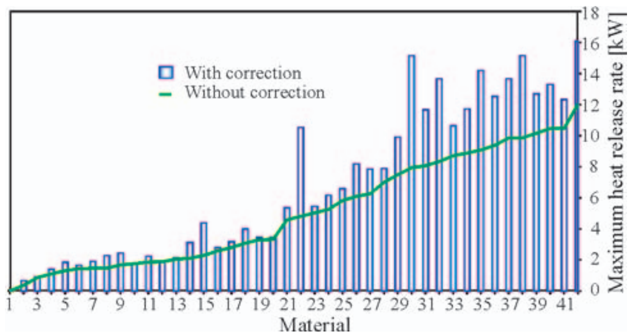

Fig. 9. *Comparing results of maximum heat release rate tests, with and without dynamic error correction*

Results recorded by the author in the tests performed on 42 materials allow a conclusion to be formulated that the relative dynamic errors of the heat release rate measurement are significant (2%÷120%). An average value of these changes for the tested group of materials equals 39%.

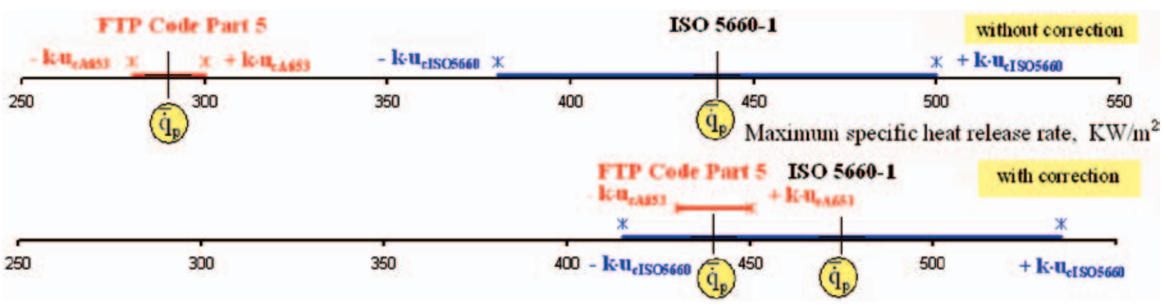

Fig. 8. *Heat release rates obtained for WO7 wool carpet using ISO 5660-1 (50 kW × m^{-2}) and FTP Code Part 5 (Res. A.653(16)) methods, and taking into account measurement uncertainty.*

The highest dynamic error is recorded for materials that are characterized by low resistance to external ignition sources, and fast acceleration of the thermal decomposition and combustion process (Fig. 10, 11 and 12).

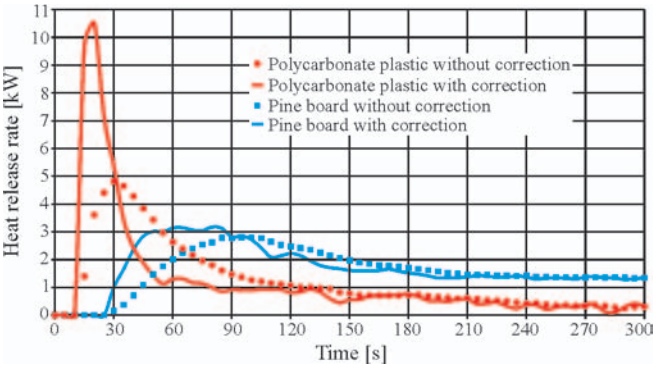

Fig. 10. *Time-history of heat release rate fluctuations taking into account dynamic correction of the station for polycarbonate panel of 2 mm thickness and for pine board of 20 mm thickness, according to FTP Code Part 5 (Res. A.653(16)) method*

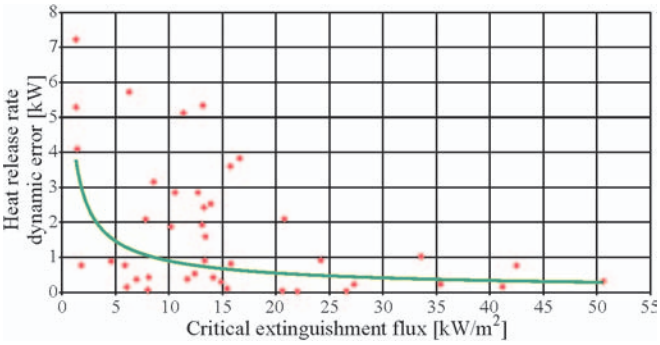

Fig. 11. *Dynamic error for materials of different critical extinguishment flux values defined by FTP Code Part 5 (Res. A.653(16)) method*

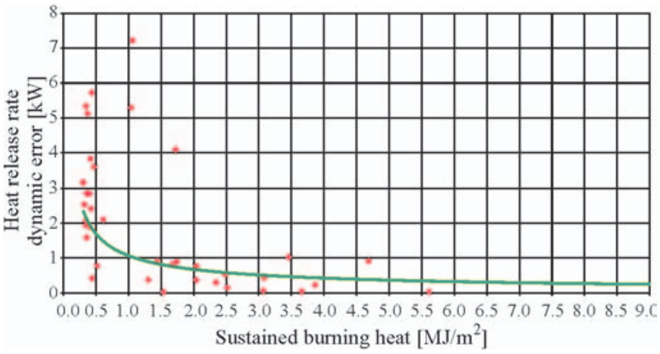

Fig. 12. *Dynamic error for materials of different flame combustion support heat values defined by FTP Code Part 5 (Res. A.653(16)) method*

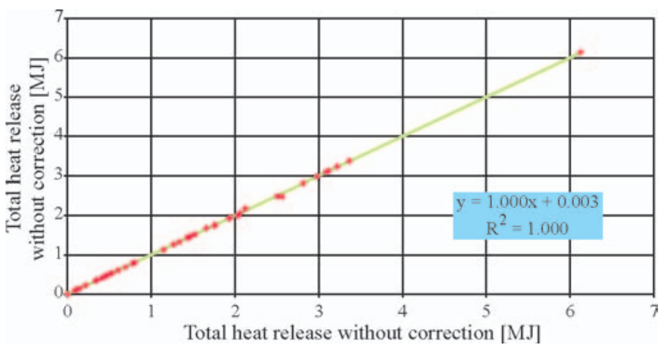

Fig. 13. *Effect of dynamic error correction on the volume of the heat released during the test*

The influence of the dynamic error (fig. 11 and 12) for wall and ceiling materials characterized by slow surface flame propagation (KSP ≥ 20 kW·m^{-2}, Q_{sb} ≥ 1.5 MJ·m^{-2}), which are used in shipbuilding, is not significant. However, for floor finish materials characterized by slow surface flame propagation (KSP ≥ 7.0 kW·m^{-2}, Q_{sb} ≥ 0.25 MJ·m^{-2}), also used in shipbuilding, the influence of the dynamic error should be taken into account (fig. 11 and 12).

Comparing the results of author's research performed on 42 materials according to FTP Code Part 5 (Res. A.653(16)) method has revealed (fig. 13) that the proposed method of heat release rate dynamic error correction does not affect the measured value of the released heat (both the inclination ratio and the correlation ratio equal 1.000).

This way the requirement of correct operation of the dynamic error corrector was fulfilled. The areas below the heat release rate time-histories with and without dynamic error correction are equal. The volume of the thermal energy released during the research is strictly defined and it should not depend on procedures used for converting the intermediate results of the measured quantity. This is a basic advantage of the dynamic correction method applied to heat release rate measurements making use of ISO 5660-1 and FTP Code Part 5 (Res. A.653(16)).

The applied method of measurement result correction reduced the differences between the maximum heat release rate values determined using the two methods. At the same time, it did not affect the measured heat value.

The proposed improvement [8] of the heat release rate research method taking into account dynamic parameters of the station according to FTP Code Part 5 (Res. A.653(16)) may be widely used in shipbuilding. Production and repair shipyards make use of significant volumes of materials and articles for ship interior design and furnishings, which, according to the regulations in force, have to reveal slow surface flame propagation. 42 materials and articles typically used on ships were selected to check the usefulness of the proposed modification to the research method defined by FTP Code Part 5 (Res. A.653(16)), and the possible effect of this change on the obtained results.

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