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A risk-based approach to developing design temperatures for vessels operating in low temperature environments

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ABSTRACT

Increasing activities in the Arctic and Antarctic waters have drawn awareness of the risks of shipping in these regions. Winterization of vessels needs to be considered at the design stage to mitigate the risk of icing, freezing or other damages due to low temperature. The temperature that should be used for design and equipment procurement specification must be defined. Classification societies have proposed design temperatures such as the design service temperature (DST) and the minimum anticipated temperature (MAT). The DST is selected to be at the lowest mean daily average for the operational window and geographical location. However, there is very limited guidance provided to define the MAT. The lack of analytical tools that can be used to develop design temperatures still remains a problem.

This paper proposes a risk-based approach to estimate minimum anticipated temperature as design temperatures for vessels intended for service in cold regions such as the Arctic and Antarctic. Hourly air temperature data from climatology stations in these regions were obtained from the website of the National Climatic Data Center (NCDC) which is affiliated to the National Oceanic and Atmospheric Administration (NOAA). The criteria used to select the stations include the time span of available data for at least 20 years, availability of hourly data, and altitude of the station (close to sea level). The analysis procedure involves statistical analysis, consequence quantifications and risk calculations.

Results from a case study show that the proposed methodology can be reasonably applied. As the minimum anticipated temperature was obtained by looking at the smallest risk with corresponding larger return period or the smallest probability of occurrence. It is expected to have the smallest risk when the minimum anticipated is applied. In addition, an extreme low temperature contour map of the Arctic region has been developed which provides a quick and useful way to evaluate the temperature profile for voyage planning and winterization requirements. A plot of the ship's route on the extreme low temperature contour map will provide information on the magnitude and duration of the extreme temperatures encountered by the ship during the journey.

1. Introduction

Recent years have seen increasing activities in the high latitude regions of the world (Transport Canada, 2010; Environment and Natural Resources, 2012; Morse, 2012). The number of ice-classed vessels has dramatically increased with more frequent transportation in the cold regions, such as the Arctic, Northern Sea Routes, Northwest Passage, Eastern Baltic, Sakhalin, Snovhit and some places in the Antarctic (ABS, 2009). The harsh environment of these regions places additional challenges on the design and operation of these vessels. The low temperatures may affect functioning of vessel systems and consequently cause safety problems (Yang et al., 2013; ABS, 2009). Poorly developed design temperatures can cause catastrophic consequences if the system does not function reliably when the temperature is low. Therefore, it is important to define temperatures to verify that structures and systems are designed to the appropriate level for the intended service environment. Design temperature requirements may potentially affect operational limitations of vessel systems, material selection for structure and machinery, selection of equipment and testing regimes. For instance, material grades need to be selected based on design temperature, material class and thickness.

In this paper, the design temperature is the minimum anticipated temperature established based on measured data from the vicinity where the vessels will be operating. All vessel systems should be designed and manufactured to operate at this temperature. The most recognized definition of a design temperature is from the

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International Association of Classification Societies (IACS) Unified Requirement (UR) S6 for structural steel to be serviced at low temperature. IACS-UR-S6 requires that the design service temperature (DST) be selected as the lowest mean daily average temperature (LMDAT) for the operational window and geographical location. Use of the LMDAT as a design temperature has been widely accepted and practiced for many years. ABS (2010) requires that the DST be applied to the vessel structural material, e.g., the structural steel, and the minimum anticipated temperature (MAT) be used for machinery. The MAT can be defined by the designer, owner, or operator or taken as 20 °C lower than the DST. However, there is very limited guidance available to define the MAT rationally. In some circumstances, vessel systems may be exposed to the low temperature that occurs for only a few minutes. It may not be necessary to design or winterize the entire system using such a temperature because the duration of the cold occurrence could be too short to reduce safety levels. The development of design temperature as minimum anticipated temperature is a complicated problem and currently there is lack of effective tools that can be used.

Sulistiyono et al (2014) have proposed a new and more rational approach to estimate the MAT in a graphical format called the Temperature-Duration-Frequency graph or TDF graph. The new approach of estimating MAT using the TDF graph can statistically answer the chance of occurrence of extreme temperatures for a given duration. They provided the details of the development of TDF graphs and provided sample TDF graphs for selected weather stations in the Arctic region. The work presented herein is an extension of Sulistiyono et al (2014).

Safety must be prioritized when operating in remote and cold regions with limited resources and longer rescue time. To ensure safe operations, it is reasonable to develop minimum anticipated temperatures considering risk as a key factor. Risk analysis is helpful to reduce conflict between cost, schedule, and safety goals that manifest routinely in management decision-making (Faber, 2007). Goerlandt et al. (2015) have developed a risk-informed ship collision alert system in a real-time operational environment. Dong and Frangopol (2015) have used the life-cycle risk associated with flexural failure as one of the criteria to develop inspection and maintenance strategies of ship structures. A risk-based approach to winterization of vessels has been proposed and applied to a North Atlantic-based ferry design (Yang et al., 2013, 2015). This paper proposes a risk-based approach to estimate a minimum anticipated temperature whose value incorporates both the probability of a low temperature occurrence and the duration of its occurrence. Vessel systems will be designed and manufactured for service at this temperature specification. This paper is structured as follows. The next section will start with a brief discussion of the concept of risk followed by the proposed methodology. A demonstration of the proposed approach is then applied in a case study. Finally, conclusions are provided in the last section.

Authors wish to confirm that intention of this work is to provide a scientific basis for an alternative approach to establishing a temperature for a given operational period and location; it may be used to establish a value used as the Minimum Anticipated Temperature (T_{MAT} or MAT) as defined in the ABS *Guide for Vessels Operating in Low Temperature Environments* (ABS, 2010).

2. Proposed methodology

The concept of risk will first be discussed. Considering an activity with only one event with potential consequences *C*, the risk *R* is the probability *P* that this event will occur multiplied by *C* given the event occurs (Faber, 2007). In Pate (2007), probabilistic risk analysis (PRA) has been discussed in detail to include probabilities of conditional events characterized by several levels. The method proposed by Pate (2007) has inspired this study to estimate a risk based minimum anticipated temperature for Arctic and Antarctic Shipping and Offshore Operations with 3 levels of conditions: Probability of Occurrences, $P(O)$, Duration of Occurrences (D) and Probability of Exceedances, $P(E)$. In this study, risk is defined by the probability of loss due to the exceedance of the minimum anticipated, and therefore referring to the concept of risk and Eq. 1, risk is estimated using Eq. (1):

$$\text{Risk} = P(O) \times C \tag{1}$$

where the probability of occurrence, (i.e., the probability of the event that more extreme temperatures are encountered than the estimated extreme temperature for a given return period) can be calculated using Eq. (2):

$$P(O) = \frac{n}{N} \times \frac{1}{RP} \tag{2}$$

where n is the number of the times that more extreme temperatures are encountered than the estimated extreme temperature for a given return period; N is the total number of temperatures in the whole data set; and RP is the return period of the estimated extreme temperature (i.e., a recurrence interval of the extreme temperature).

And consequences, C can be estimated using Eq. (3), which represent the severity of the consequence through the duration of the extreme cold temperature occurrence:

$$C = D \times P(E) \tag{3}$$

where $P(E)$ is the annual exceeding probability (i.e., the inverse of the return period). A further explanation on the above equation is presented in *Step* 8.

Therefore, risk can be calculated using Eq. (4):

$$Risk = P(O) \times D \times P(E) \tag{4}$$

where D is duration of averaged temperatures and $P(E)$ is probability of exceedance which can be determined from a fitted distribution and a return period.

Next, the steps to be followed for the proposed risk-based approach to estimating minimum anticipated temperature will be discussed. The steps start from determining the route to be taken by the vessel to estimating the risk-based minimum anticipated temperature. Fig. 1 gives the flowchart of the proposed methodology. Each step is described in the following paragraphs.

Step 1: Determining the region of operation or route of vessel

It is important to determine the region of operation or the route to be taken by a vessel because every region or route might have a different climatic condition including the extreme low temperatures to be encountered. Cold environments with the presence of ice at times require special ship designs, navigation skills and winterization level and technology. Information about the region of operation or the route of a ship can be obtained from the owner of the ship or from ship route maps. Some well-known routes that have been voyaged by ships include the Northeastern Passage or the Northern Sea Routes, Northwestern Passage, the Arctic Bridge and along the Southern Ocean (Clarkson Research Service Ltd., 2013; Anonymous, 2010).

Step 2: Determine the period of operation in the harsh environment

Ships operating in the Polar Regions are most likely in the summer season when there is open water. The period of shipping operation is often obtained from the shipping schedules. While for ship design, the period of shipping operation can be obtained from the time series plot of temperature data for the year. Fig. 2 shows an