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Monitoring Thermal Conditions and Finding Sources of Overheating †

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Abstract: This research defines a method for detecting the source of thermal heating in a cargo container by monitoring surface temperature and through reverse engineering of the thermal process. A simplified heat direct model in 3D space was formulated and the inverse model wa olved using the theory of hypernumbers.

Keywords: information; temperature; heat; source; hypernumber

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1. Introduction

Cargo fires and explosions often happen due to self-heating [1]. Self-heating occurs when an exothermic (heat-producing) chemical or biochemical reaction starts within a body of cargo. Monitoring thermal conditions in a container with cargo is important for detecting the source of overheating. It is a challenging problem due to the complexity of three-dimensional heat exchange models, which provide information about the behavior of the cargo [2,3]. Finding the source of overheating will allows us to predict dangerous thermal situations and events. This task is critical for multiple situations such as air cargo transport safety, protecting pharmaceutical products from spoiling, and preventing fire. The list of overheating causes includes:

a. Calcium hypochlorite and other solids oxidation. The self-decomposition of such solids can evolve self-heating process. This can lead to "thermal runaway".
b. Biomass heating due to the rotting process, in which methane concentration is produced. "Anaerobic" rotting can produce dangerous concentrations of methane and lead to explosion.
c. The decomposition of fertilizers in the bulk with the evolution of heat.
d. Lithium battery heat release due to natural discharge.
e. Liquid monomers polymerization which evolves heat. Self-heating normally occurs in localized hot spots within a bulk cargo and identifying events by temperature measurement is a challenging problem.

The described solution monitors container temperatures at defined points, solving the ill-posed problem of re-engineering temperature transfer in a 3D space with insulated boundary conditions. The heat exchange in the package of the batteries could be approximated with a composed heat rate coefficient. The direct model of heat exchange with pointed heat source in a semi-infinite body is developed in [2]. The model can be extended for bounded 3D spaces. Such an extension is given below. The location of the source can be found by resolving the ill-posted problem using the minimum least square criterion and finding a solution to the non-linear system of the equations with the hypernumber method [4–7]. In this work, we focus on detecting the pointed sources of overheating in homogeneous media or such that with some approximation can be assumed as homogeneous.

Our model of inverse engineering for locating the source of heating and predicting transient temperature distribution inside the container has several computational advantages:

- It is a simplified direct model for calculating the heat propagation from a pointed source in a three-dimensional space.
- The inverse model uses a hypernumber recursive analytical method, which is much faster in comparison with the utilized numerical methods. Thermodynamic parameters, which in most cases are not known, or the values, which cannot be estimated precisely, are calculated based on inverse re-engineering definitions.
- The hypernumber method guarantees the convergence of the process.
- Due to the relative simplicity of the algorithm, the computation can be implemented using inexpensive controllers such as, for example, Atmega 2560. The time of calculation using embedded *C* would be in a range of a tenth of milliseconds. This approach can be generalized to the cases when the heat exchange is not the same in all directions.

2. Direct Model of the Heat Transfer in a Cargo Container

The three-dimensional heat transfer model from the pointed source is derived from the one-dimensional heat transfer model [2];

$$
\begin{aligned}
dT(x,y,z,t) = {} & \frac{dq}{\gamma C(4\pi a\pi(t-t_0))^{\frac{3}{2}}} e^{-\frac{(x-x_s)^2+(y-y_s)^2+(z-z_s)^2}{4a(t-t_0)}} + \\
& \frac{dq}{\gamma C(4\pi a\pi(t-t_0))^{3/2}} e^{-\frac{(x-x_s)^2+(y-y_s)^2+(z+(h-z_s))^2}{4a(t-t_0)}} + \\
& \frac{dq}{\gamma C(4\pi a\pi(t-t_0))^{3/2}} e^{-\frac{(x-x_s)^2+(y+(b-y_s))^2+(z-\ z_s)^2}{4a(t-t_0)}} + \\
& \frac{dq}{\gamma C(4\pi a\pi(t-t_0))^{3/2}} e^{-\frac{(x+(a-x_s))^2+(y-y_s)^2+(z+z_s)^2}{4a(t-t_0)}}
\end{aligned}
\tag{1}
$$

where a—diffusivity, γ—density of the heat transfer medium, dq—delta thermal heat, $x_s,\ y_s,\ z_s$—coordinates of the heat source.

Considering the steady rate of the heat, the temperature at time t can be found as:

$$
\begin{aligned}
T(x,y,z,t) = {} & \int_0^t \frac{pd\tau}{\gamma C(4\pi a\pi(\tau-t_0))^{3/2}} \left(e^{-\frac{(x-x_s)^2+(y-y_s)^2+(z-\ z_s)^2}{4a(\tau-t_0)}} + \right. \\
& e^{-\frac{(x-x_s)^2+(y-y_s)^2+(z+(h-z_s))^2}{4a(\tau-t_0)}} + \\
& \left. e^{-\frac{(x-x_s)^2+(y+(b-y_s))^2+(z-\ z_s)^2}{4a(\tau-t_0)}} + e^{-\frac{(x+(a-x_s))^2+(y-y_s)^2+(z+z_s)^2}{4a(\tau-t_0)}} \right)
\end{aligned}
\tag{2}
$$

3. Reverse Engineering of the Heat Source with the Theory of Hypernumbers

The source of heating $A(x_s,\ y_s\ ,\ z_s)$ can be found with the Least Square algorithm

$$
A(x_s,\ y_s\ ,\ z_s) : U = min \sum_{i=0}^{m=amoint\ of\ sensors} \sum_{j=0}^{n} \left(T^a_{i,j} - T^m_{i,j}\right)^2 \tag{3}
$$

where $T^a_{i,j}$—is the analytically defined temperature at the time moment with index j at temperature sensor j location, $T^m_{i,j}$—is the monitoring temperature at the time moment with index j and sensor m.

$$
F_1 = \frac{\partial U}{\partial x_s} = 2\sum_0^m \sum_{j=0}^n \left(T^a_{i,j} - T^m_{i,j}\right) \frac{\partial T^a_{i,j}}{\partial x_s} = 0 \tag{4}
$$

$$F_2 = \frac{U}{\partial y_s} = 2\sum_{0}^{m}\sum_{j=0}^{n}\left(T^a_{i,j} - T^m_{i,j}\right)\frac{\partial T^a_{i,j}}{\partial y_s} = 0 \tag{5}$$

$$F_3 = \frac{\partial U}{\partial z_s} = 2\sum_{0}^{m}\sum_{j=0}^{n}\left(T^a_{i,j} - T^m_{i,j}\right)\frac{\partial T^a_{i,j}}{\partial z_s} = 0 \tag{6}$$

$$F_4 = \frac{\partial U}{\partial p} = 2\sum_{0}^{m}\sum_{j=0}^{n}\left(T^a_{i,j} - T^m_{i,j}\right)\frac{\partial T^a_{i,j}}{\partial p} = 0 \tag{7}$$

$$F_5 = \frac{\partial U}{\partial a} = 2\sum_{0}^{m}\sum_{j=0}^{n}\left(T^a_{i,j} - T^m_{i,j}\right)\frac{\partial T^a_{i,j}}{\partial a} = 0 \tag{8}$$

The $(x_s)_m$, $(y_s)_m$, $(z_s)_m$, γ_m, a_m are solutions defined with hypernumbers in Equations (9)–(12)

$$(x_s)_m = H_n((x_s)_m)_{m\in\omega} \tag{9}$$

$$(y_s)_m = H_n((y_s)_m)_{m\in\omega} \tag{10}$$

$$(z_s)_m = H_n((z_s)_m)_{m\in\omega} \tag{11}$$

$$\gamma_m = H_n(\gamma_m)_{m\in\omega} \tag{12}$$

$$a_m = H_n(a_m)_{m\in\omega} \tag{13}$$

The equations for the hypernumber deviations $\{\delta(x_s)_m,\ \delta(y_s)_m,\ \delta(z_s)_m,\ \delta\gamma_m,\ \delta a_m\}$ are defined below

$$\begin{pmatrix} \delta F_{1,m+1} \\ \delta F_{2,m+1} \\ \delta F_{3,m+1} \\ \delta F_{4,m+1} \\ \delta F_{5,m+1} \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} \\ d_{41} & d_{42} & d_{43} & d_{44} & d_{45} \\ d_{51} & d_{52} & d_{53} & d_{54} & d_{55} \end{pmatrix} \times \begin{pmatrix} \delta(x_s)_m \\ \delta(y_s)_m \\ \delta(z_s)_m \\ \delta\gamma_m \\ \delta a_m \end{pmatrix} = \begin{pmatrix} (1-\ \theta)F_{1,m} \\ (1-\ \theta)F_{2,m} \\ (1-\ \theta)F_{3,m} \\ (1-\ \theta)F_{4,m} \\ (1-\ \theta)F_{5,m} \end{pmatrix} \tag{14}$$

The coefficients $d_{i,j}$ are calculated with Equations (15)–(19)

$$d_{i,1} = \frac{\partial F_i}{\partial x_s} \tag{15}$$

$$d_{i,1} = \frac{\partial F_i}{\partial y_s} \tag{16}$$

$$d_{i,1} = \frac{\partial F_i}{\partial z_s} \tag{17}$$

$$d_{i,1} = \frac{\partial F_i}{\partial x_s} \tag{18}$$

$$d_{i,1} = \frac{\partial F_i}{\partial x_s} \tag{19}$$

Using Equations (3)–(19) was written software that shows the accurate results of solving the inverse problem with artificial simulation of the heat source.

4. Conclusions

The described method for detecting thermal threats in a cargo container would allow essentially improving the safety of cargo transportation.

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