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Development and illustration of a computationally convenient App for simulation of transient cooling of fish in ice slurry at sea

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ABSTRACT

The use of ice slurry at sea to cool fish is widespread. Here we develop and illustrate a convenient simulation of fish cooling in ice slurry based on the transient cooling equation together with practical simplifying assumptions. It is convenient because the key input is the mass of the fish, which is routinely measured, and because it can be solved in standard spread-sheeting tools as a portable App. It is planned this innovative App would be calibrated for use in particular fisheries. Illustrative simulations for Southern BlueFin Tuna (*Thunnus maccoyii*) (SBT) show that a 35 kg fish at harvest ($T_i = 28$ °C) will cool to 5 °C (at thermal centre) in 10.23 h in slurry at a temperature maintained at 0 °C. Because predictions are demonstrated to be in good agreement with published Heisler charts it is concluded the simulation is free of programming and computational errors. Importantly, simulations reveal a small rise in the temperature of the slurry significantly affects the time for cooling. For example, if the temperature of the slurry rises to 2 °C, because of inadequate quantities of ice, the time to cool the SBT to 5 °C will be 12.27 h.

1. Introduction

The cooling of freshly harvested fish in ice slurry at sea is almost universal in the fishing industry (Davey, 2012; Graham, Johnston, & Nicholson, 1992, chap. 3, 75 pp.; Granata, Flick, & Martin, 2012, pp. 251–ff; Huss, 1995, chap. 7, 195 pp.; Shawyer & Medina Pizzali, 2003, chaps. 4, 7, 108, pp.). Ice slurry is a mix of crushed or flaked ice with a small amount of water to make the mixture just mobile and to provide intimate contact between the surfaces of the fish and pieces of ice (Bellas & Tassou, 2005; Huss, 1995, chap. 7, 195 pp.). The slurry is intended for rapidly cooling the fish but not as a means of storage. It is harmless to fish taste and texture (Graham et al., 1992, chap. 3, 75 pp.). When properly used, it can keep fish fresh for long periods so that they remain attractive to wholesalers. A freshly harvested fish is one that is has been caught, bled, gilled, gutted and cleaned (Davey, 2012). To ensure sufficient amounts of ice are on hand at sea to cool the day's fish catch a number of predictive approaches have been made. These include the calculation methods of Graham et al. (1992), chap. 3, 75 pp.; Huss (1995), chap. 7, 195 pp. and Shawyer and Medina Pizzali (2003), chaps. 4, 7, 108, pp. and, more recently, that of Davey (2012).

However a major need of fishermen at sea is to know the time it will take for the fish in the catch to be cooled in the ice slurry to an acceptable (regulatory) temperature (at the thermal centre) (Anon, 2005, 2006; Graham et al., 1992, chap. 3, 75 pp.; Venugopal, 2006). Clearly, in a mixed catch of fish, the bigger (greater mass) will take longer than the smaller to cool in the slurry. A number of methods have been reported to predict cooling of individual fish, for example, those of Lin, Cleland, Cleland, and Serrallach (1996), Zhao, Kolbe, and Craven (1998) and Jain, Ilyas, Pathare, Prasad, and Singh (2005). These can however suffer drawbacks because Newtonian cooling (that is "lumped thermal capacity" Holman, 2002, pp. 31–ff, 511–ff, 675–ff) is assumed (Jain et al., 2005; Jain & Pathare, 2007), or, they need a high level of mathematical sophistication (Lin et al., 1996; Zhao et al., 1998) for solution and application. These therefore have not been widely taken up for use by fisherman at sea.

1.1. This research

Against this background a generalised and computationally convenient simulation of the cooling time of fish has been developed for fishermen and boat owners who use ice slurry to cool fish at sea. It is based on a fundamental solution of the transient (unsteady) cooling equation together with practical assumptions. The simulation is convenient because the key input is the mass of the harvested fish, which is readily and routinely measured at sea, and

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Nomenclature

a, b	constants, Eq. 11
A_B	constant, dimensionless, Eq. 1
Bi	Biot number, dimensionless, Eq. 4
C_B	constant, dimensionless, Eq. 1
C_f	heat capacity of fish, J kg^{-1} K^{-1}, Eq. 7
F	fat content, % w/w, Eq. 12
Fo	Fourier number, dimensionless, Eq. 6
h	heat transfer coefficient (convection resistance), W m^{-2} K^{-1}, Eq. 4
$J_0(), J_1()$	Bessel functions of the First Kind, dimensionless, Eq. 5
k_f	thermal conductivity of fish (conduction resistance), W m^{-1} K^{-1}, Eq. 4
K	characteristic constant for a particular fish species at harvest, m$^{-1/2}$, Eq. 8a
L_f	characteristic length of a particular fish species at harvest, m, Eq. 8a
m_f	mass of fish at harvest, kg, Eq. 8
M	moisture content, % w/w, Eq. 12
s	characteristic radius of a particular fish species at harvest, m, Eq. 1
t	time for fish in ice slurry to reach T_0, h, Eq. 1
T_0	target (centreline) temperature of cooled fish, °C, Eq. 2
T_S	ice slurry (convection environment) bulk temperature, °C, Eq. 2
T_i	initial (conduction environment) uniform temperature of fish °C, Eq. 3
V_f	characteristic volume of fish at harvest, m^3
Greek symbols	
α_f	thermal diffusivity of fish, m^2 s^{-1}, Eq. 1
ϑ_0	target temperature difference ($T_0 - T_S$), K, Eq. 2
ϑ_i	initial temperature difference ($T_i - T_S$), K, Eq. 3
ρ_f	density of fish, kg m^{-3}, Eq. 7
Other	
SBT	Southern Bluefin Tuna (*Thunnus maccoyii*)

because the simulation is presented as an "App" (Anon, 2012b) in standard spread-sheeting tools to give an immediate quantitative output for a wide range of users. Illustrative simulations are then presented and discussed for Southern BlueFin Tuna (*Thunnus maccoyii*) (SBT), an economically important and premium fish grown in Australia for export. Predictions when compared with established Heisler charts (Heisler, 1947; Holman, 2002, pp. 31–ff, 511–ff, 675–ff; Schneider, 1955, pp. 213, 1963, pp. 213) show good agreement and it is concluded therefore the App is free of computational and programmable errors. The established simulations are used to underscore the significant impact small rises in temperature of the slurry will have in increasing the time for cooling and to highlight the need to maintain the slurry at the lowest equilibrium temperature with adequate amounts of prepared ice. The research will be of immediate benefit to fishermen and boat owners and agents who use ice slurry to cool and preserve fish.

2. Model development

2.1. The equations

Consider a freshly harvested fish of mass, m_f, at a uniform initial body temperature, T_i, suddenly (Bairi & Laraqi, 2003) immersed in ice slurry at a bulk temperature, T_S (All terms used are carefully defined in the Nomenclature at the end of this paper). It is assumed that:

i. There is sufficient ice so that the slurry bulk temperature, T_S, does not change with time i.e. sufficient ice is available to prevent it all from melting in the slurry (The ice-to-fish mass ratio required can be reliably obtained for example from the method of Davey (2012))
ii. The harvested fish can be modelled as a cylinder of radius, s, on which any end effects are negligible
iii. There is adequate mixing of ice, water and fish.

This type of heat problem is defined as transient conduction with surface convection (Holman, 2002, pp. 31–ff, 511–ff, 675–ff), that is, heat energy moves from within the fish to the fish surface by conduction and is carried away to the bulk slurry by convection.

The temperature-time profile of interest during cooling in ice slurry is that at the centre of mass of the fish, that is, the centreline temperature, T_0, of the assumed equivalent cylinder (radius, s). This will be the point of slowest cooling in the fish mass. The solution for the centreline temperature of a cylinder with transient cooling, to within one percent, is given by Schneider (1955), pp. 213, (1963), pp. 213 and Heisler (1947) as:

$$\frac{\theta_0}{\theta_i} = C_B \exp\left(-A_B^2 \frac{\alpha_f t}{s^2}\right) \tag{1}$$

where two temperature difference terms are defined as:

$$\theta_0 = T_0 - T_S \tag{2}$$

$$\theta_i = T_i - T_S \tag{3}$$

C_B and A_B are constants that are defined using Bessel Functions, $J_0()$ and $J_1()$, of the First Kind (Abramowitz & Stegun, 1972, chap. 9–ff; Heisler, 1947; Schneider, 1955, pp. 213, 1963, pp. 213) such that:

$$\frac{A_B J_1(A_B)}{J_0(A_B)} = Bi = \frac{hs}{k_f} \tag{4}$$

and

$$C_B = \frac{2}{A_B}\left(\frac{J_1(A_B)}{J_0^2(A_B) + J_1^2(A_B)}\right) \tag{5}$$

where Bi = Biot number, h = convective heat transfer coefficient from the fish to the bulk slurry and k_f = thermal conductivity of the fish.

The Bi number defined in Eq. (4) is seen to compare the surface-convection with internal-conduction resistances to heat transfer (Holman, 2002, pp. 31–ff, 511–ff, 675–ff). A low value of Bi (typically < 0.1) means that the internal conduction resistance is negligible compared with the surface convection resistance. In Eq. (1) the term:

$$\frac{\alpha_f t}{s^2} = Fo \tag{6}$$

where Fo = Fourier number, t = time elapsed in the slurry, and α_f = thermal diffusivity of the fish, which is defined by: