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Insulating properties of styrofoam boxes used for transporting live fish [1]

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Abstract

Tropical fish are shown to be adapted to temperatures between 22–30°C and temperatures below 15–18°C are known to cause mortalities. Insulating properties of standard Styrofoam boxes used for shipping live fish were examined. The following equation can be used to estimate the change in water temperature over time in relation to box type, water volume/surface, water temperature and ambient temperature: $T_{W_e} = T_{Air} + (T_{W_b} - T_{Air}) \cdot e^{-(t \cdot I \cdot W_s / W_v)}$, where T_{W_e} is the water temperature in degrees Celsius at the end of time interval t; T_{Air} is the ambient air temperature; T_{W_b} is the water temperature at the beginning of time interval t; W_S is the water surface in cm^2; and W_V is the water volume in ml. I is the insulation coefficient and can be estimated as follows: $I = W_V \cdot W_S^{-1} \cdot (\ln T_{db} - \ln T_{de}) \cdot t^{-1}$, where T_{db} is the difference in temperature between water and air at the beginning of time interval t, and T_{de} is the difference in temperature between water and air at the end of the time interval. The average insulation coefficient for a standard Styrofoam box with 2.5 cm wall thickness and filled with about 8 ℓ water is $I = 0.11$. The total surface area of the water in the box can be determined as follows: $W_S = 2 \cdot B_{Li} \cdot B_{Wi} + 2 \cdot W_V / B_{Wi} + 2 \cdot W_V / B_{Li}$, where W_S is the surface area in cm^2, B_{L_i} is the inner length and B_{W_i} is the inner width of the box in cm. Using thicker Styrofoam boxes or increasing insulation by other means is appropriate during Northern Hemisphere cold spells. Adding bags with hot water is less effective, but may be chosen when other means are not available. A better designed, cube-shaped Styrofoam box is suggested as the most promising and cost-effective measure to reduce mortalities resulting from heat loss during transport. © 1998 Elsevier Science B.V.

Keywords: Fish transport; Water temperature; Mortality; Styrofoam boxes; Insulating properties

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1. Introduction

The trade in ornamental fish from tropical Asia, Africa and South America to Europe and the USA is a multimillion-dollar business. For example, it is estimated that aquarists in the UK keep about 140 million pet fish and support annual fish imports of about US$20 million (OFI., 1996). Over US$500 million worth of ornamental fish are imported into the USA each year (Shariff and Subasinghe, 1992). For transport, fish are packed in plastic bags filled with one-third water and two-thirds oxygen and then shipped in Styrofoam boxes by air-freight; duration of transport is usually about 24 h from exporter to importer station (Froese, 1985a, 1986, 1988). Styrofoam boxes are the transport media of choice because they are light, insulating, watertight, reasonably robust and relatively cheap. Tropical fish are adapted to temperatures between 22–30°C (Fig. 1); they are vulnerable to temperatures below 20°C and mortality will occur at temperatures below 15–18°C (Kausch, 1972; Strange, 1980; Shafland and Pestrak, 1982; Boedi Mranata, 1984; Behrends et al., 1990; Bennet and Judd, 1992; Bly and Clem, 1992; Chow et al., 1994; Starling et al., 1995). Fish are more affected by decreasing than by increasing temperature (Fernandes and Rantin, 1986; Klyszejko et al., 1993; Segnini de Bravo et al., 1993). A fast drop in temperature from 25°C to 9°C will kill most tropical fish within 1 h (Boedi Mranata, 1984). Juvenile fish are more sensitive to low temperatures than are older fish (Shekk et al., 1990). Conversely, coldwater fish are stressed when the temperature of the transport water increases (Peterson and Anderson, 1969; Kilgour et al., 1985; Davis and Parker, 1990; Korsmeyer, 1991; Eaton et al., 1995).

During air transport, sensitive shipments such as live fish are stored in temperature-controlled sections of the cargo bay with temperatures between 20–27°C (Lufthansa Manila, personal communication). Air shipments are exposed to ambient temperatures

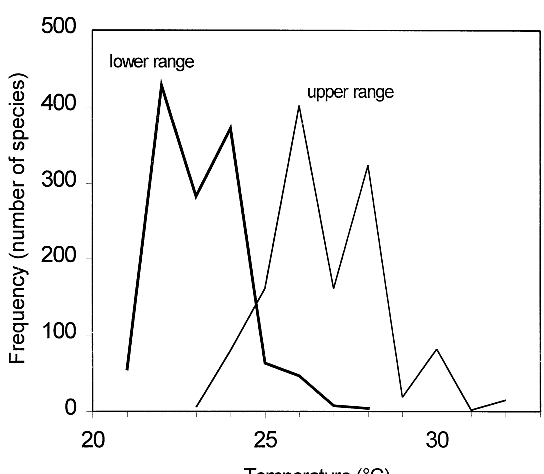

Fig. 1. Preferred temperature ranges of 1254 tropical fishes, based on data in the March 1997 version of FishBase (Froese and Pauly, 1996).

for several hours when they are transported and temporarily stored at the destination airport, while waiting for connecting flights or customs clearance. During the winter this may result in temperate areas in a significant drop in water temperature and increased mortality rates of up to 100%, with considerable economic losses. For example, this study was initiated by a request of a German court to assist in a case where a German importer had sued a South American airline because a shipment of 120 boxes arrived with water temperatures well below 15°C and mortality rates over 50%. Applying the equations given below indicated that the time between landing and arrival at the importer's station was not sufficient to have caused the observed drop in water temperature, even when it was assumed that the boxes had been exposed to outside air temperature for that duration, indicating that the cargo hold of the plane may not have been heated sufficiently.

The trade meets such problems by extra insulation efforts such as: wrapping the Styrofoam boxes in foam rubber or plastic sheets and putting them into cardboard boxes; including bags with hot water wrapped in paper inside the Styrofoam boxes; using thick Styrofoam boxes, such as those normally used to ship frozen food. All these measures add considerably to shipping costs.

The present study examines the insulating properties of several standard Styrofoam boxes and provides an equation to estimate the change in water temperature in relation to box type, water volume/surface, water temperature, and expected ambient temperature.

2. Material and methods

Five types of standard Styrofoam boxes were used for the experiments (Table 1). Plastic bags were filled with a specified volume of tap water and a temperature sensor was placed inside the bag, connected by a thin cable to an external display unit. The bags were sealed with a rubber band and placed each in one box. The boxes were closed and sealed with tape to prevent any exchange of air, as is common practice in the trade. The boxes were put on a table in a temperature-controlled chamber such that top and sides were freely exposed to ambient air. Water and air temperature were recorded at about hourly intervals for the duration of the experiment.

The amount of energy necessary to increase the temperature of a given substance per unit mass by 1°C is called specific heat with the unit: J kg^{-1} $°C^{-1}$. Of all known substances, water has the highest specific heat (Trautwein et al., 1978). In comparison, the thermal capacity of the air enclosed in the Styrofoam boxes is negligible. Change in temperature over time of a body with a given mass is described by Eq. (1) (after Eckert, 1959):

$$\mathrm{d}Q/\mathrm{d}t = I \cdot W_S \cdot T_d \tag{1}$$

where, in this case, Q is the amount of energy lost to ambient air, per unit mass; I is an empirical factor describing the insulation characteristics of the Styrofoam boxes and the special conditions of the experiment such as wind or continuously shaking of the boxes; W_S is the water surface through which temperature is exchanged; and T_d is the

Table 1
Outer and inner dimensions, wall thickness, inner volume, surface area of water and ratio between surface and volume·1000 for five different types of styrofoam boxes used in the experiments

Box type	Inner dimensions			Wall (cm)	Inner volume (l)	5-l Surface (cm^2)	Water ratio	6-l Surface (cm^2)	Water ratio	8-l Surface (cm^2)	Water ratio	10-l Surface (cm^2)	Water ratio
	L (cm)	*W* (cm)	*H* (cm)										
A	35	35	19	2.0	23.3	3021	0.60	3136	0.52	3364	0.42	3593	0.36
B	37	37	22	2.5	30.1	3279	0.66	3387	0.57	3603	0.45	3819	0.38
C	41	35	31	2.5	44.5	3400	0.68	3506	0.58	3717	0.47	3929	0.39
D	44	29	33	2.5	42.1	3124	0.63	3239	0.54	3467	0.43	3696	0.37
E	46	33	25	5.0	38.0	3556	0.71	3661	0.61	3869	0.48	4077	0.41
F	33	33	33	2.5	35.9	2784	0.56	2905	0.48	3147	0.39	3390	0.34

Box type F is a proposed design with an improved surface-to-volume ratio.

difference between water temperature and ambient air temperature. Integration and rearrangement of Eq. (1) gives:

$$T_{W_e} = T_{Air} + \left(T_{W_b} - T_{Air}\right) \cdot e^{-(t \cdot I \cdot W_s / W_v)} \quad (2)$$

where T_{W_e} is the water temperature at the end of time interval t in degrees Celsius; T_{Air} is the ambient air temperature; T_{W_b} is the water temperature at the beginning of time interval t; I is the insulation coefficient (see above); W_S is the water surface in cm^2; and W_V is the water volume in ml. Note that Eq. (2) will also estimate an increase in water temperature if the ambient air is warmer than the water in the box.

The total surface area of a given volume of water depends on the shape of the box and can be determined as follows:

$$W_S = 2 \cdot B_{Li} \cdot B_{Wi} + 2 \cdot W_V / B_{Wi} + 2 \cdot W_V / B_{Li} \quad (3)$$

where W_S is the surface area in cm^2; B_{Li} the inner length and B_{Wi} the inner width of the box in cm. For the box types used, the corresponding surface areas are given in Table 1.

To determine the insulation coefficient, Eq. (2) can be rearranged as follows:

$$I = W_V \cdot W_S^{-1} \cdot (\ln T_{db} - \ln T_{de}) \cdot t^{-1} \quad (4)$$

where T_{db} is the difference in temperature between water and air at the beginning of time interval t, and T_{de} is the difference at the end.

Eq. (4) was used to determine the insulation coefficient for Box Types A, B, C, D and E in the various experiments.

To simulate transport conditions such as wind and handling, boxes of Type B were exposed to constant air flow (2–3 m/s) and shaking (50 cpm).

3. Results and discussion

Altogether 19 experiments were conducted. The experimental conditions included box type, water volume, the duration of the experiment, water temperature at the beginning of the experiment, average air temperature during the experiment, and initial difference between water and air temperature (Table 2). Special conditions included a fan aimed at the boxes to increase temperature exchange through convection, and shaking of the boxes to simulate transport conditions. The calculated insulation coefficient I for these experiments ranged from 0.077 (= more insulation) to 0.133 (= less insulation) (Table 2).

3.1. Experimental setup

Water temperature decreased exponentially during feasibility experiments 3 and 4 (Table 2; Fig. 2). The initial temperature difference of 0.7°C between Boxes 1 and 2 remained nearly the same, with 0.6°C difference after 22 h and a decline in water temperature of 5.4 and 5.5°C, respectively. The air temperature averaged about 15°C

Table 2
Experiments conducted to determine the insulation coefficient (I) for various types of styrofoam boxes and different experimental conditions, sorted by box type, water volume and temperature difference between water and air at the beginning of the experiment

Experiment	Box type	Water volume (1)	Water–air (°C)	Water start (°)	Water end (°)	Air average (°C)	Duration (h)	Insulation coefficient (I)	Remark
1	A	6	20.4	24.4	10.8	4	21.9	0.096	
2	A	5	13.6	23.6	13.5	10	19.8	0.113	
3	B	10	8.8	23.8	18.4	15	21	0.119	
4	B	10	9.5	24.5	19	15	21	0.108	
5	B	10	13.6	23.6	15.4	10	22	0.110	
6	B	8	19.8	23.8	10.6	4	21.9	0.111	
7	B	6	14.4	10.6	21.7	25	24	0.109	
8	B	6	15.1	9.9	21.2	25	24	0.102	
9	B	6	18.6	22.6	7.8	4	24	0.117	Fan
10	B	6	18.8	22.8	7.1	4	24	0.133	Shaking
11	B	6	19.2	23.2	8.4	4	23.7	0.100	Fan
12	B	6	19.5	23.5	9	4	21.9	0.110	
13	B	5	13.5	23.5	13.3	10	22	0.098	
14	C	10	14.3	24.3	16.5	10	19.8	0.101	
15	D	6	15.6	9.4	20.6	25	24	0.098	
16	D	6	18.7	22.7	8	4	24	0.119	
17	E	6	15.5	9.5	20	25	24	0.077	
18	E	6	19.9	23.9	9.8	4	21.9	0.092	
19	E	6	20.3	24.3	10.2	4	24	0.081	

See text for further details.

during the experiment. Curves calculated with Eq. (2) and shown in Fig. 2 matched the observed values. Thus, the setup was considered suitable for the intended experiments.

3.2. Effect of water surface

For a given volume of water, the change in temperature over time will be less if the water surface can be minimized (see Eq. (1)). For rectangular Styrofoam boxes, the water surface would be least if the water in the box formed a cube. As can be seen in Table 1, the ratio between surface area and volume, one of the exponents in Eq. (2), decreases with increasing volume of water, especially in Box Type A, which has a square footprint. It seemed that an ideal Styrofoam box would have a square bottom and be three times higher than wide, so that a box filled with one-third water and two-thirds oxygen would contain a perfect cube of water. However, such a box would be difficult to handle and might be stored accidentally sideways, achieving quite the opposite of what was intended. Also, the contact area between water and oxygen in the plastic bag is important for gas exchange and minimizing it may lead to other problems. Styrofoam boxes that resemble a cube might be a good compromise (see below).

3.3. Styrofoam wall thickness

The boxes used in the experiments were of 2, 2.5 and 5.0 cm wall thickness (Table 1). Box Type E with its double wall thickness of 5.0 cm had the lowest coefficient

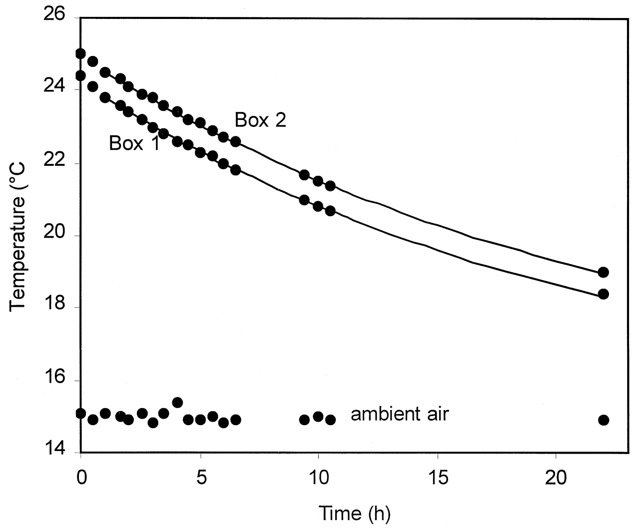

Fig. 2. Decrease of temperature of 10 l water with Styrofoam boxes of 2.5 cm wall thickness, with ambient air temperature of 15°C (experiments 3 and 4 in Table 2). Observed values are plotted. Lines were calculated by Eq. (2), starting after 1 h.

($I = 0.077$–0.092, average $= 0.083$; see Table 2) and thus provided the best insulation. Despite a wall thickness of 2 cm only, Box Type A had the second best insulation coefficient ($I = 0.096$–0.113, average $= 0.105$), probably due to its small and square footprint (Table 1). The average insulation coefficient for Styrofoam boxes B, C, and D in experiments 3–16 (Table 2) was determined as $I = 0.110$, with 95% confidence limits at 0.104 and 0.115.

3.4. Emulating transport conditions

A fan aimed at the boxes did not lead to a notable change in the insulation coefficient. Results of fan experiments 9 and 11 ($I = 0.110$–0.117) overlap with those of experiments 12 and 16 ($I = 0.110$–0.119), which were conducted under very similar conditions, but without a fan.

Shaking Box Type B in experiment 10 resulted in a markedly higher value ($I = 0.133$) for the insulation coefficient when compared with experiments 9 ($I = 0.117$), 11 ($I = 0.110$), 12 ($I = 0.110$) and 16 ($I = 0.119$), which were conducted under very similar conditions but without shaking. Shaking most probably increased temperature exchange by constantly mixing the water and thus increasing the active surface area between water and ambient air.

3.5. Manipulating water temperature

While exporters have little influence on ambient air temperature once the shipment has passed customs, they may, for example raise the temperature of the transport water prior to shipment. This, however, might be counterproductive because an increase in temperature also increases fish metabolism and thus creates additional stress (Froese, 1985b; Chow et al., 1994).

Adapting fish to lower temperatures prior to shipment has been suggested to reduce metabolism and stress (Vollmann-Schipper, 1975). However, during the winter this will lead to even lower water temperatures on arrival, and the logistics of maintaining cold water in tropical countries and readapting the fish to their normal temperatures at the importer's station might cause yet more problems and mortalities. Thus, it seems best to ship fish in clean water at the temperature in which they were kept at the exporter's station.

3.6. Adding 'hot bags'

No experiments have been conducted on the common practice of placing small bags with hot water wrapped in paper ('hot bags') inside the Styrofoam boxes, normally placed between the transport bags, but sometimes placed at the bottom or in the corners of the box. However, some generalizations can be derived from Eq. (1). First, it is important that the hot bags exchange their temperature directly with the transport water. This is determined by the contact area between hot bags and transport water. Thus, placing hot bags at the bottom or in the corners of the Styrofoam box exchanges only about one-fourth of the temperature with the transport water and the rest is lost to ambient air.

The maximum possible effect of hot bags on the temperature of the transport water can be estimated using Eq. (5) (modified after Trautwein et al., 1978):

$$T_d = (W_{Vt} \cdot T_{Wt} + W_{V\,hb} \cdot T_{W\,hb}) / (W_{Vt} + W_{V\,hb}) - T_{Wt} \qquad (5)$$

where T_d is the maximum heat increase that the hot bag can produce, W_{Vt} is the volume of the transport water in liters, T_{Wt} is the initial temperature of the transport water; W_{Vhb} is the volume of water in the hot bag in liters, and T_{Whb} is the initial temperature of the water in the hot bag.

For example, a hot bag with 1 l of water of 50°C placed in a box with 10 l of transport water of 25°C will increase water temperature by at most 2.3°C. The actual increase will be less, because the contact area between hot bag and transport water will be less than 100% and thus probably more than a quarter of the energy will be lost directly to ambient air. Most of this exchange will happen during the initial hours of transport when it is actually unwanted. Wrapping the hot bag in several layers of paper may delay this exchange to some extent. This method is expensive because it increases the weight and thus the cost of the shipment by about 10%.

3.7. Changing box design

Given a choice, exporters should opt for cube Styrofoam boxes of 2.5 cm or more wall thickness and with an inner volume of 30–42 l. Such a box allows for 10–14 l of water per box, which is the amount normally used in the trade and is apparently, the maximum weight that a Styrofoam box of 2.5 cm wall thickness can hold safely. Table 1 gives the dimensions and surface-volume ratio for such a hypothetical box (Type F). Note that the water surface-to-volume ratio is improved by 6–27%, compared with the other boxes. Everything else being as stated in Table 2, the improved ratio would reduce the change in temperature of experiments 1–19 by 4–12% (0.4–1.7°C).

4. Conclusions

A better designed Styrofoam box might be the most promising and cost-effective measure to reduce fish mortalities resulting from heat loss during transport. Using thicker Styrofoam boxes or increasing insulation by other means is appropriate during cold spells. Adding bags with hot water is probably less effective, but may be chosen when other means are not available. When average durations and temperatures of the various sections of a planned transport are known, exporters can use Eq. (2) for each section to calculate the water temperature at arrival for typical and for ‘worst case’ scenarios.

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