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Newton's law of cooling and its interpretation

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ABSTRACT

This paper will show that so-called "Newton's law of cooling" that is often used for calculating of heat transfer by convection is actually not a law, but a model of heat exchange (heat transfer). Limits of validity of this law were discovered and will be shown. Moreover, an existing practice of modernizing this law for the purpose of calculating convective heat transfer will be questioned.

1. Introduction

In the 18th century Isaac Newton [1] studied cooling of different kinds of solids. Independently from him a Russian scientist of German origin, Georg Wilhelm Richmann [2] conducted numerous experiments on cooling of spherical glass vessels, filled with water of different temperatures. Although Richmann's experiments were conducted almost 50 years later than Newton's, he learnt about Newton's studies only after he finished his own. Because his experiments were as much varied and informative as Newton's, Richmann contributed greatly to the modern definition of law of cooling. That is why in Russia Newton's law of cooling is called Newton–Richmann law of cooling.

In theory and practice of heat transfer mechanisms' calculations the efforts of the researchers are often directed to the definition of a value called "heat transfer coefficient". Usually this value is experimentally defined from the Newton law of cooling. In theoretical constructions (that are more often than not are just approximations), the Fourier's law along with a compulsory use of the Newton law of cooling is used for calculation of the heat transfer coefficient. Because of the importance of the Newton's law, it is necessary to establish the limits of its validity.

As a rule, all laws of physics (theories and models) are valid only under certain conditions. The reason for this is that it is necessary to disregard any interactions not essential to the course of the studied phenomenon while separating a certain physical system from a surrounding world. The Newton's law of cooling is not an exception. Knowing the limits of validity of the law (or a model) allows us to avoid its incorrect application. The purpose of this paper is to discover conditions that make possible to use the Newton's model, and also to establish validity of using a similar dependence in the theory and practices of convective heat transfer.

2. Theoretical questions

Newton's law of cooling suggests that the intensity of energy transfer in the form of heat depends on a difference of temperatures of the interacting physical systems. Linear character of this dependence is widely accepted. In its modern version it is written out as (1)

$$q = \alpha(T_w - T_\infty), \tag{1}$$

here q – the heat flux (W/m^2); T_w – temperature of the heating surface (wall temperature) (K); T_∞ – ambient temperature (K); α – an empirical value called "heat transfer coefficient" (W/(m^{2}K)).

Expression (1) is a generalization of experiments by Newton [1], and also a generalization of independent and more detailed numerous experiments by Richmann [2].

This is how Richmann conducted his experiments: «I suspended on a thin cord a spherically-shaped glass vessel with a narrow neck in such a way that it was touching only air at temperature 68 F, and then poured boiling water in this vessel .... After lowering the thermometer into the water, I saw that the heat had decreased ...» [2, p. 73]. The temperature was measured in degrees of Fahrenheit and was recorded every five minutes. Experiments were conducted with different amounts of water.

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Nomenclature

List of symbols

L	some constant (1/K)
N	number of particles in mole
p	pressure (*Pa*)
Q	the energy in the form of heat (J)
q	surface flow density of the heat flux (W/m^2)
T	temperature (K)
T_w	temperature of the heating surface (wall temperature) (K)
T_∞	ambient temperature (K)
U	internal energy (J)
V	volume (m^3)
x	distance (m)

Greek letters

α	an empirical value called "heat transfer coefficient" (W/(m$^2 \cdot$ K)
β	some constant (1/m)
γ	energy of one mole (J/mol)
λ	thermal conductivity (W/(m $\cdot$ K))

Subscripts

w	wall condition
∞	ambient condition

From the conclusions of the paper: «Thus we conclude from the experiments that the heat decrease ... occurs as complex dependence, varying in direct proportion to surfaces and differences between the temperatures of cooled or heated masses and air temperature, and in inverse proportion to volumes of heated or cooled masses, provided that the time intervals are equal each other and not too large. When we confirm this hypothesis, we will be capable to validate the law, according to which it will be possible to predict heat decrease or increase for any time interval **at a constant air temperature**» [2, p. 80] (emphasized by me).

Unfortunately, his tragic death prevented Georg Richmann to write down the law in the form of (1). But it is important to note that during his experiments the indoor temperature of the room where they were conducted (ambient temperature T_∞) remained the same at all times.

From here follows the first and very important restriction of the Newton's law of cooling: stability of the ambient temperature during the heat exchange. This stability is possible only under certain conditions. According to the first law of thermodynamics (2), for open systems containing one mole of substance, the energy in the form of heat δQ is spent for changing of internal energy dU, execution of work pdV, and mass transfer γdN

$$\delta Q = dU + pdV + \gamma dN, \tag{2}$$

here p – pressure (*Pa*); V – volume (m^3); γ – energy of one mole (J/mol); N – number of particles in mole.

The room (lab), where experiments are usually conducted, is generally an open system. If a sufficient amount of heat δQ is supplied, the system becomes stationary with invariable internal energy. In this case supplied superfluous energy is spent on execution of work and mass transfer. For regular lab rooms (not hermetically sealed) the system's possibilities for execution of work and mass transfer are limited by the sizes of walls, doors, windows, and degree of their air-tightness. If, after achieving stationary condition, we to increase supply of sufficient heat, the system will come to a new stationary condition, but with a higher level of internal energy. Thus, indoor air temperature (ambient temperature T_∞) will grow to a new value.

Both in the Newton's law of cooling and in our everyday thinking temperature T_∞ is a temperature of the environment rather far removed (formally, even infinitely removed) from the borders of the examined physical system. On some borders, where heat sources or heat drains exist, the temperature can be more or less than T_∞. However, when moving farther and farther away from them, it acquires value T_∞ that corresponds not to the equilibrium value in the thermodynamic sense, but to a static value (probably, it can be called "dynamically equilibrium value T_∞"). Numerical value T_∞ may depend on many causes. For example, it may depend on the ability of the system to absorb heat (thermal capacity). It may depend on a type of a heat exchange process (p = *const*; V = *const*, etc.), or on a method of heat transfer (by convection, heat conductivity, or emission). Very important, it may also depend on the number of particles creating the system (number of mols).

If a stationary system with temperature T_∞ engages in thermal interaction with another system, similar to a glass sphere (as in Richmann's example), the energy transferred from the sphere may be not enough to change the ambient temperature in the room T_∞. The temperature, as it is usually defined today, is a measure of an average kinetic energy of a chaotic movement of a system particle. To calculate it, one has to divide the energy coming from the sphere by the enormous number of particles creating the system (the air particles in the lab). Because the spheres in the experiments were small in size and had relatively low temperatures, their energy was not sufficient to change temperature T_∞. On a sphere surface the temperature T was higher than T_∞ ($T > T_\infty$), but it quickly decreased along with distance x from a surface, and in the large distance (theoretically $x \to \infty$) became equal $T = T_\infty$. This situation resembles a cooling process of a cup of tea in a room, or an ocean where isolated ships (for example, aircraft carriers) are drifting. They emit heat, but this energy is not enough to change ocean's temperature as a whole.

Let us emphasize that the Newton's law of cooling in the form of (1) in essence describes an attenuation of a weak disturbance (heated sphere that is not capable of changing room's temperature). In case of a strong (powerful) thermal disturbance (for example if, instead of small sphere as Richmann did, we are to place a large barrel of near boiling water in the lab), the room temperature will not remain the same any more. Will expression (1), describing the attenuation of a weak disturbance, be fair in this case of a changing system (temperature growth)? Many types of growth processes conform to the exponential rule. On the other hand, it is usually possible to linearize, approximate, or replace with linear function any function in a neighborhood of some value. Therefore, the answer to this question, as usual, requires conducting experiments.

It is important to notice that the relation (1) connects three independent values: heat flux q, wall temperature T_w, and stable during heat exchange process ambient temperature T_∞. In this form the relation (1) makes a claim to be called a law. However, it does not follow from this law how large should be a distance $x(m)$ from the wall when the value of the temperature T_w is established. One can assume that this distance is not too large. It means that the change of temperature with distance x from a wall may comply, for example, with the law $T(x)$ in the form of (3)