The First Law of Thermodynamics in Vector Form and Convective Heat Transfer

Davidzon Mikhail Yosifovich

School of General and Theoretical Physics, Physics Department, Ivanovo State University, Ivanovo, Russia

Email address:
davese@mail.ru

Abstract: Nowadays most of the practical calculations and theoretical findings in convective heat transfer amount to determining heat transfer coefficient (a coefficient of proportionality between surface density of the heat flux and temperature difference between the wall and the heated medium). An expression that includes heat transfer coefficient is called Newton's law of cooling. The purpose of this study is to show that Newton's law of cooling is not consistent with the first law of thermodynamics, and the study proves it using a new, vector form of the first law of thermodynamics, along with the more traditional scalar form. The study also offers a new analytically obtained expression for calculating surface density of the heat flux, and shows that it is not consistent with the Newton's law of cooling. It also shows that Fourier's thermal conduction law is a consequence of the first law of thermodynamics in vector form, and that Fourier-Richmann's law of cooling and Newton's law of cooling do not agree with the first law of thermodynamics. The results of this study can be used in engineering calculations for heat-using devices, as well as in a theoretical research. Additionally, the study suggests a new possible way to derive a nonlinear energy equation – by using vector form of the first law of thermodynamics. If previously obtained nonlinear Navier-Stokes equation is added to this nonlinear energy equation, a system of nonlinear equations could be obtained to correctly describe theory and practice of convective heat exchange, introducing completely new methods for calculating convective heat exchange (without using traditional heat transfer coefficients and laws of cooling).

Keywords: First Law of Thermodynamics, Heat Transfer Coefficient, Newton's Law of Cooling, Surface Heat Flux Density

1. Introduction

Traditionally, researchers describe the phenomenon of convective heat transfer using a system of differential equations (Navier-Stokes equation, continuity equation, energy equation), and also an expression describing proportionality of the heat flux surface density to the wall-liquid temperature difference (Newton's law of cooling). A coefficient of proportionality in the Newton's law of cooling is called "heat transfer coefficient" (convective heat exchange coefficient). Scientists and engineers spend a lot of their time and effort calculating this variable, although not much can be found in scientific and technical literature to substantiate validity of Newton's law of cooling. Nobody is mentioning any law of physics from where Newton's law of cooling followed, and often heat transfer coefficient is even called "an ancillary variable".

It would make much more sense that a description of thermal phenomena (including convective heat transfer) should be based on the laws of thermodynamics, meaning that mathematical expression of the Newton's law of cooling and the energy equation both must follow from the laws of thermodynamics. That is why this paper is trying to use the first law of thermodynamics to obtain an expression for the heat flux surface density instead of the Newton's law of cooling.

2. On Vector and Scalar Forms of the First Law of Thermodynamics

Quantitative description of processes shows that some quantities can be conserved under certain conditions, and there are more than one and a half dozen conserved quantities in physics. Conserved quantities and conditions under which they exist are described by conservation laws. In mechanics

there are laws of conservation of momentum, angular momentum, and mechanical energy, where each of these variables measures the quantity of mechanical motion. The laws of conservation also help to solve various problems in physics. If conservation laws apply, from the initial state of a physical system we can find its final state without the describing the whole process in detail. Conservation laws can be also written out for thermal motion, but in this case it would be necessary to calculate the quantity of thermal motion.

In classical physics each type of motion can have a scalar or a vector measure of motion. A system's quantity of motion can be determined by studying the system's influence on another system during their interactions. For example, if a moving ball runs into a stationary ball, then, as a result of interaction, the second ball moves. Quantity of motion of each system can be determined by change in velocity and change in moving direction of each of the balls.

Starting with Descartes in the 17th century, scientists tried to describe quantity of mechanical motion quantitatively. Some suggested using as a measure momentum (product of mass and velocity), others suggested using kinetic energy. And only in the second half of the 20th century Sorokin [1] proposed a theory that stated that in classical physics there are two quantities of mechanical motion, correlating to space and time: vector (momentum), and scalar (kinetic energy). Nowadays not only Newton's second law of motion [2] can be written out for each of these two quantities, but laws of conservation of vector and scalar quantities of motion can be written out too.

For some reasons quantity of motion usually is not used when describing heat phenomena, perhaps due to the nature of the heat systems. However, the more quantities of motion exist, the more conservation laws would exist, and, consequently, the greater number of computational equations would be needed for calculations – that's why thermal phenomena are so difficult to quantify. For this reason, in contrast to the deterministic description of Newton's classical mechanics, when studying thermal phenomena it would make sense to introduce microparameters and their averaged values in the form of macroparameters, because thermodynamic systems are indeterministic (probabilistic). Classification of systems into open systems (capable of exchanging mass and energy with the environment), closed systems (capable of exchanging only energy with the environment), and closed-loop systems adds additional complexity to the formulation of conservation laws. Thus, the usual formula of the first law of thermodynamics for closed systems (the energy supplied to the system in the form of heat dQ is spent on the change in the internal energy of the system dU, and doing the work PdV) needs to be adjusted if the thermodynamic system is open. In this case, it is necessary to take into account the change in energy of the system as a result of the entering or leaving system's N particles with the energy γ of one particle. Then the first law of thermodynamics can be written out in the form of (1):

$$dU = dQ - PdV + \gamma dN \qquad (1)$$

Equation (1) is written in scalar form. If to assume as a

scalar measure for the thermal motion the energy of the particles making up the system (internal energy U), then the expression (1) can be described as following: the internal energy of the system dU is spent on energy transfer through heat exchange, making work, and energy changing due to particles entering or leaving the system.

A thermodynamic system can also be located in the action field of different forces (gravity, electromagnetic, or surface forces). Then on the right side of equation (1) it is necessary to take into account a change in internal energy due to the interaction with the external forces and fields. Subsequently, in each specific case, the law of the internal energy change would look different.

The first law of thermodynamics then becomes an equation (or the law) describing a change in a scalar measure of thermal motion (or its internal energy), just as like an assumption in mechanics that a change in kinetic energy is equal to the work of forces (the second Newton's law in scalar form). In mechanics, both scalar and vector measures of motion depend on velocity. To move from one measure of motion to another, we need to divide kinetic energy by velocity.

In thermal interactions the amount of heat energy transferred or received depends on the surface area where heat is transferred. The area can be vectorized to give it direction. If we divide the energy transferred in the form of heat in one second by the surface area, we will get a vector variable: surface density of the heat flux q.

To quantitatively determine vector measure of thermal motion q, let's ask a question: what would q depend on? If to assume that surface density of the heat flux would depend on the temperature gradient ∇T, physical properties of the medium λ, characteristic size of the system L, and velocity v (in case of convective media). So, $q = q(\nabla T, \lambda, L, v)$. Then the increment of the function q can be written out in the form of expression (2):

$$dq = \frac{\partial q}{\partial \nabla T} d\nabla T + \frac{\partial q}{\partial \lambda} d\lambda + \frac{\partial q}{\partial L} dL + \frac{\partial q}{\partial v} dv \qquad (2)$$

For a system with dimensions and physical properties being unchanged in the process of heat transfer, expression (2) can be simplified, and it would turn into (3):

$$dq = \frac{\partial q}{\partial \nabla T} d\nabla T + \frac{\partial q}{\partial v} dv \qquad (3)$$

Expression (3) is indeed the first law of thermodynamics in vector form. For systems where velocity is absent or constant, the second term on the right becomes equal to zero. To solve the differential equation (3) in the approximation in question $dv = 0$, it is necessary to know the expression for the partial derivative with respect to the temperature gradient.

If one to assume that

$$\frac{\partial q}{\partial \nabla T} = \lambda = const,$$

then the first law of thermodynamics in vector form takes the form of (4):

$$dq = \lambda\, d\nabla T \qquad (4)$$

To emphasize that this is a vector form of the first law of thermodynamics, equation (4) can be written out in vector notation:

$$d\vec{q} = -\lambda \, d\overrightarrow{\nabla T}$$

The solution of the equation (4) under the condition $q = 0$ and when $\nabla T = 0$ leads to the Fourier's law of heat conduction (5):

$$q = \lambda \nabla T \qquad (5)$$

From the formal (mathematical) point of view, expression (5) can be seen as an expansion of the unknown function q in the Maclaurin series. When expanding, a linear approximation of the function was used: the function was replaced by a tangent to it with a close to zero value of the argument (temperature gradient). In other words, the solution of the equation (4) in the form of (5) is valid for even extremely small temperature gradient. For example, when liquids are heated, temperature gradient is zero in channels on the channel axis, but as it approaches the walls, temperature gradient increases sharply. However, although Fourier's law is valid near the channel's axis, it doesn't work near the channel's walls.

To write out the expression for the heat flux density that would be valid over the entire cross-sectional area of the channel, it is possible, for example, to increase the number of expansion terms in the Maclaurin series. Another way would be to take into account the parameters that affect the surface density of the heat flux. By definition, surface density of the heat flux q (heat energy transmitted per unit of time and sent to the heat exchange surface) includes a change in the internal energy. The change in the internal energy grows along with the increasing temperature. According to Fourier's law, surface density of the heat flux is proportional to the temperature gradient. So, it looks like the surface density of the heat flux depends on the temperature of the body and on the temperature gradient: $q(T, \nabla T)$. However, it would be not be correct to say that the increment of this function is equal to the sum

$$dq = \frac{dq}{dT} dT + \frac{dq}{d\nabla T} d\nabla T$$

In classical physics and mathematics a function is usually expressed in terms of independent arguments. But in our case, temperature and temperature gradient are not independent arguments. If temperature field is known, then temperature gradient can be determined by differentiation. If a temperature gradient is given, then we can find temperature distribution in space by integration. Thus, the expression for the heat flux surface density must include either temperature or temperature gradient.

To satisfy the temperature requirement, let's assume that the partial derivative of the heat flux density over the temperature gradient is not a constant (as is usually believed in the linear theory of convective heat transfer), but is a power function (6), in which B and n are some constants:

$$\frac{\partial q}{\partial \nabla T} = B \nabla T^n \qquad (6)$$

It seems that n can take on the same values (from -1 to 0), as in [3]. In this case, the first law of thermodynamics in vector form can be written out as the expression (7):

$$dq = B \nabla T^n d\nabla T \qquad (7)$$

Let's solve equation (7) under the same conditions as before, and we'll find out that q is not a linear function of (8):

$$q = \frac{B}{n+1} \nabla T^{n+1} \qquad (8)$$

Expression (8) is consistent with Fourier's law – when medium's velocity equals zero and $n = 0$, expression (8) becomes indistinguishable from Fourier's law of heat conduction.

Consequently, to solve heat exchange problems, it is possible to either use the first law of thermodynamics (1) written in scalar form, the expression (8) that follows from its vector form (4, 7), or a combination of both.

3. The Laws of Cooling and the First Law of Thermodynamics

At present time, the expression (9) (called "Newton's law of cooling" in English-language literature or "Newton-Richmann's law" in Russian-language literature) is the one most often used in solving convective heat transfer problems:

$$q = \alpha(T_w - T) \qquad (9)$$

Here q is surface density of the heat flux, α - heat transfer (heat exchange) coefficient, T_w is wall temperature, T is liquid temperature.

Different researchers define liquid temperature T in different ways. Heat transfer textbooks [4-6] call it "a temperature of a liquid or gaseous medium surrounding a body." Other scientific literature clarifies that it can be a temperature of the liquid located far from the channel wall, or a constant liquid temperature along the channel cross section [7], or an average liquid temperature along the channel cross section [8]. Some even argue that each problem should specify what is meant by T: an average temperature over the channel cross-section, or an average mass temperature of the liquid, or even a constant temperature of the liquid across the channel section at the inlet to the heated section of the channel. They believe that the choice would depend on the nature of the problem and calculating convenience [8].

Even the expression (9) is called "Newton's law of cooling," Newton actually did not suggest dependencies similar to (9). But in experiments on cooling a body [9-11] he could not help but notice that the higher would be the temperature of the cooling body, the more energy per unit of time would be transferred into the environment. To make the experiments more clear-cut, he always cooled the body in the same way – by using constant-speed air flow. It seems that he was interested in the relationship between the amount of heat

released into the environment and the temperature of the cooling body. The simplest assumption here would be a linear dependence. It seems to us that exactly this statement about the proportionality between the amount of heat transmitted by the heated body and its temperature ("*the total heat of iron*") [11] is the main point of the "true" Newton's cooling "law" (or hypothesis).

If U is denoted as the energy lost by the heated body upon cooling, and t is denoted as time, then the Newton's law of cooling can be written in the form (10),

$$\frac{dU}{dt} = kT_w \qquad (10)$$

where k is the coefficient of proportionality, T_w is the body temperature (can also be body surface temperature).

If to keep in mind that in Newton's experiments the mass of the heat-releasing body (iron bar) basically did not change, and the specific thermal capacity C at a constant volume is a constant in this case, then instead of (9) (11) can be written out as

$$dU = mCdT_w \qquad (11)$$

If one to compare expression (9) with expressions (10) and (11), it would be quite obvious that they are not the same. If we call expression (10) the "true" Newton's law of cooling, then the expression (9) can be called "fictitious" Newton's law of cooling.

In thermodynamics expression (11) presents a method of calculating internal energy of a physical system. In this case the temperature is measured using Kelvin's units on the absolute thermodynamic temperature scale. So, it looks like that the "true" Newton's law of cooling (10) establishes a fundamental thermodynamics connection between the quantity of thermal motion of the system's particles (system's internal energy) and temperature, and not just any temperature – the absolute temperature. In those times Newton's contemporaries used different temperature scales that were often not compatible, which, perhaps, prompted Newton to search for a convenient, "universal" temperature scale. Unfortunately, the researchers never noticed this Newton's innovation, and only in the 21st century Kartashov [12] pointed out to Newton introducing absolute temperature in his studies back in his day.

Richmann [13] also studied the processes of cooling and heating. The results of his experiments [13] on the cooling of small glass spheres filled with hot water can be represented in modern interpretation in the form of the dependence (12):

$$q = \sigma(T_w - T_\infty) \qquad (12)$$

Here σ is the empirical coefficient, T_∞ is the ambient air temperature (room temperature where the experiments took place).

Fourier [14] was interested in studying the same processes, too, and also suggested several laws including cooling and heating phenomena. In his famous "Analytical Theory of Heat" [14] in order to describe the intensity of heat transfer he used a notion of a heat flux density q as the amount of heat transmitted per unit of time through the surface. He also proposed two ways of determining q: first, if a homogeneous solid body is placed between two limitless surfaces that have different, but not changing with time temperatures, then the dependence (5) (Fourier's thermal conduction law) should be used to calculate heat flux density. Second, in a case of heat transfer from a moving liquid, Fourier proposed another way of calculating heat flux surface density: if there is a heat transfer from a surface with a constant temperature T_w to the room air with a constant temperature T_∞, then the surface density of the heat flux should be determined using the dependence (13):

$$q = \sigma_1(T_w - T_\infty) \qquad (13)$$

Here σ_1 is some constant (external conductivity), T_w is the temperature of the heated surface, T_∞ is ambient air temperature. If it is assumed that air velocity near the surface does not change during the heat exchange, then σ_1 would also be a constant.

Fourier also noted that the constant σ_1 should be different for different media, should depend on temperature, and can also be determined experimentally. So, it is easy to see now that Fourier's law does not differ much from Richmann's cooling law (12), so it would make sense to call it the "Fourier-Richman's cooling law".

Now let's compare expressions that are corollaries from the first law of thermodynamics with the other known cooling laws. Since thermodynamic systems can be substantially different, let's consider the simplest case: a liquid is being heated in the channel in the absence of fields, phase transitions, and doing work. In this case, the first law of thermodynamics in scalar form (1) would simply look as

$$dQ = dU$$

In vector form, the same law can be written out in different forms (4) and (7). Table 1 shows the expressions for cooling laws and the first law of thermodynamics in this simple case.

Table 1. The first law of thermodynamics and the laws of cooling.

Law	Scalar form	Vector Form	Corollary of law
The first law of thermodynamics	$dQ = dU$	$dq = \lambda\, d\nabla T$ $dq = B\nabla T^n d\nabla T$	$q = \lambda\, \nabla T$ $q = \frac{B}{n+1}\nabla T^{n+1}$
Fourier's thermal conduction law		$q = \lambda\, \nabla T$	
Fourier-Richmann's cooling law		$q = \sigma_1(T_w - T_\infty)$	
"Fictitious" Newton's cooling law		$q = \alpha\,(T_w - T)$	
"True" Newton cooling law	$dQ = dU$		

Here are several conclusions that can be drawn from the comparison of the laws presented in Table 1. The "true" Newton's cooling law is consistent with the first law of thermodynamics in scalar form, but all other cooling laws

differ from it in scalar and vector forms. Also, Fourier's law of heat conduction is a corollary of the first law of thermodynamics in vector form in a special case – when thermal conductivity coefficient is a constant. So, it can be concluded that heat transfer by heat conduction takes place in media with a stable thermal conductivity coefficient at a constant temperature gradient.

While the first law of thermodynamics was formulated in the 19th century approximately 30 years after the appearance of Fourier's works, the first mentioning of a vector form of the first law of thermodynamics is probably happening now, in this study, 200 years after Fourier. We believe that Fourier's hypothesis turned out to be true and deserves to be called law, although even at a present time it is problematically to determine thermal conductivity coefficient without using Fourier's law.

It can also be concluded from Table 1 that the Fourier-Richmann's cooling law and Newton's "fictitious" cooling law are not consistent neither with the first law of thermodynamics, nor with its corollaries. This fact leads to conclusion that these laws are not very well substantiated from the physics point of view.

From the physics point of view, at least two systems usually participate in a thermal interaction. The first one loses heat to the second one, and the second one absorbs it. If one to use internal energy as a scalar measure of thermal motion, then, in accordance with the first law of thermodynamics in scalar form, the energy supplied to the system should be written out as the loss of the internal energy of the heat-losing system. At the same time, the internal energy of the heat-absorbing system will increase by exactly the same amount. At present time we usually calculate internal energy as being proportional to the temperature difference in the system after the interaction and before the interaction. It looks like two observers measure temperature differences independently, each in its own system: an observer in a heat-losing system measures temperature difference in his system, and an observer in the heat-absorbing system measures the temperature difference in his system. This means that in the heat transfer equation (both in Fourier-Richmann's cooling law and in "fictitious" Newton's cooling law) the right side should be air (or liquid) temperature difference after heating and before heating, i.e. a difference in temperatures measured in the heat-absorbing system. But these expressions show temperature difference between heat-losing and heat-absorbing systems. In other words, these cooling laws are not consistent with the first law of thermodynamics in scalar form.

And they are not consistent with the first law of thermodynamics in vector form either. According to the first law of thermodynamics, a vector measure of thermal motion is a function of the temperature gradient. But in Fourier-Richmann's law and Newton's "fictitious" cooling law there are no gradients.

Because of all this, it can be concluded that these expressions that are considered laws are actually not laws, because they contradict the law of motion conservation

(quantities of motion), i.e. they contradict the first law of thermodynamics. In the next section we will show how to write out an expression for the heat flux surface density that is consistent with the first law of thermodynamics.

4. Heat Flux Surface Density as a Function of Process Parameters and System Geometry

The results of theoretical and experimental studies on convective heat transfer are usually written out as criterial equations based on the calculation of the heat transfer (heat exchange) coefficient with the help of the expression (9). No physics laws have been mentioned that can be used in determining this variable. This leads to a possibility that calculations can be made without using heat transfer coefficient and "fictitious" Newton's cooling law.

The calculations can be simplified if variables that we're looking for are expressed in terms of parameters that determine heat transfer process. In the process of heat exchange one of the systems loses heat and another one absorbs heat. Because of that the intensity of the energy transfer process in the form of heat (energy surface flux density) can be described independently by using macroparameters of either heat-losing or heat-absorbing systems. Let's assume that there are two observers, one in the heat-losing system, and another one in the heat-absorbing system. Each of them shows the amount of transmitted energy per second referred to the square meter of the heat exchange surface q through the macroparameters of its own system. It is clear that these expressions can take different form, but numerical value of the heat flux density would be the same. If necessary, these expressions can be set equal to each other. [15, 16, 17]. Let's see how this process can be described, for example, in case of a problem of heating a moving liquid in a pipe.

An observer in a heat-losing system (for the purpose of this discussion, responsible for observing heat supply conditions) can think something like that: what would the density of heat flux depend on? It would be clear to him that only on the power of the energy source. In turn, the power of the energy source determines surface temperature T_w, i.e. the surface density of the heat flux is a function of the wall temperature $q(T_w)$. Respectively,

$$dq = \frac{\partial q}{\partial T_w} dT_w \qquad (14)$$

To find q, it is necessary to know (from assumptions or experiments) partial derivative $\frac{\partial q}{\partial T_w}$. For example, it can be assumed that the higher would be the wall temperature, the higher would be the heat flux density. This linear dependence would be the simplest one, showing that the partial derivative of the heat flux density with respect to the wall temperature is equal to a certain constant value k.

In order to solve the equation (14) it would be necessary to set the initial conditions. The simplest would be a condition

that heat flux density equals zero when temperature equals zero. From a formal point of view this condition would be acceptable, but from the physics point of view it wouldn't work, because physical systems cannot be distinguished from each other at an absolute zero temperature. And conditions are set in place just for that very reason – to distinguish one physical system from all others.

It can be also assumed that heat flux density equals zero when wall temperature equals average liquid temperature at the channel entrance, or average liquid temperature at a channel cross-section at some distance from channel entrance. In this case there will be a linear dependence between the heat flux density and the temperature difference, i.e. an equation similar to the Fourier-Richmann's cooling law. But in our problem of heating a moving liquid in a pipe this dependence should not be linear. Heating of the liquid would take place only when wall temperature is higher than the average liquid temperature along the cross-section of the channel. Heat flux density should be zero until wall temperature becomes higher than the average temperature along the cross-section of the channel, meaning that the function $q(T_w)$ must be smooth and concave.

It seems natural to assume that heat flux density increases to infinity along with the increasing wall temperature. This condition is satisfied by an exponential function whose derivative with respect to the wall temperature is equal to

$$\frac{\partial q}{\partial T_w} = q_0 k_2 e^{k_2 T_w} \qquad (15)$$

Here q_0 and k_2 are some constants.

If one to integrate equation (14) with the expression (15) under the condition that $q = 0$ (wall temperature assumes a certain value when heat transfer stops, i.e. $T_w = T$), one arrives at expression (16):

$$q = q_0 \left(e^{k_2 T_w} - e^{k_2 T} \right) \qquad (16)$$

In other words, the observer in the heat-losing system believes that the intensity of the heat loss depends on the temperature of the heating surface. As a result of the fluid moving along the channel, heat flux density decreases, as the heat-absorbing system comes into equilibrium with the heat-losing system. The equilibrium occurs when the wall temperature becomes equal to the average cross-section channel temperature. In this situation heat exchange stops, and heat flux density becomes zero. This process is perfectly consistent with the laws of thermodynamics.

If we're interested only in an average temperature of the channel cross-section, we can obtain an expression that replaces law of cooling in the form (9). It can be done in several ways – for example, using a dimensional analysis, or using the first law of thermodynamics in scalar form.

Let's assume a medium (a liquid or a gas) enters a channel with an average cross-section temperature $<T_0>$. The medium is heated through the side surface of the channel. The average temperature of the channel cross-section $<T>$ changes along the channel length from $<T_0>$ (at the channel entrance) to some value $<T>$ at a distance dx from the channel entrance. Let's also assume that the average

velocity of the medium v at the channel cross-section remains constant along the entire channel. The heat supplied to the system dQ is spent on changing internal energy, performing work pdV, and mass transfer with the environmentγdN. If to assume that heating in channel takes place in a closed system (i.e. there is no mass transfer with the environment), the work is not performed, and there is no interaction with the external fields, then all energy dQ, supplied in the form of heat, will be spent only to change the internal energy of the moving medium dU: that is, $dQ = dU$. At present, it is believed that the change in internal energy equal to

$$dU = m \cdot C \cdot d <T>,$$

where m is the heated mass, C is the specific heat at constant volume.

If the amount of heat is measured in J / s and, accordingly, the mass in kg / s, then we come to the expression (17):

$$dQ = m \cdot C \cdot d <T> \qquad (17)$$

Let's divide the left and right sides of equation (17) by the side surface of the channel (heat exchange surface area). Then at the left-hand side of (17) we'll obtain the heat flux surface density. Expression (17) then takes the form (18) [15-17]:

$$q = \frac{m \cdot C \cdot d <T>}{\Pi \cdot dx} = \frac{f}{\Pi} \rho C v \frac{d <T>}{dx}, \qquad (18)$$

where f is the channel cross-section; Π is the perimeter of the channel.

If the channel is flat with height h and width b, it would be sufficient to write in the expression (18) that $f = hb$ and $\Pi = 2(h + b)$. For a straight cylindrical pipe with the radius r expression (18) takes the form (19):

$$q = \frac{r}{2} \rho C v \frac{d <T>}{dx} \qquad (19)$$

It must be noted that as the characteristic size of the system L it is necessary to set not the whole pipe diameter, as it is sometimes done, but only ¼ of the pipe diameter. The problem of choosing characteristic size of the system is often faced by the modern researchers when presenting experimental data as a product of dimensionless numbers (similarity criteria). Various researchers offer to choose different things as L: radius of the pipe, diameter of the pipe, height of the slit of the flat channel, ½ of the height of the slit, the equivalent diameter of the channel, and an area of the channel [18]. In thermodynamic approach (as seen from expression (18)), the characteristic dimension should be set as the ratio of the cross-sectional area of the channel f to its perimeter Π.

Expressions (18) and (19) can be used to calculate distribution of an average channel cross-section temperature $<T>(x)$ if the heat flux density q is known, or, conversely, the heat flux density can be found from the known temperature distribution.

It is also interesting to notice that expression (18) resembles Fourier's law. The product of the variables in front of the temperature gradient in equation (18) has the dimensionality of the thermal conductivity coefficient, but it includes velocity.

It is possible that this product is a coefficient of convective heat conduction, in contrast to the molecular heat conduction, as in Fourier's law.

5. Conclusion

The paper proposes to write out the first law of thermodynamics not only in scalar form, but also in vector form. Using first law of thermodynamics in vector form to calculate convective heat transfer allows to derive an equation for the heat flux surface density that differs from the one used traditionally. The paper also shows that Fourier's thermal conduction law is a consequence of the first law of thermodynamics in vector form, and that Fourier-Richmann's law of cooling and "fictitious" Newton's law of cooling do not agree with the first law of thermodynamics.

The results of this study can be used in engineering calculations for heat-using devices, as well as in a theoretical research. The study also suggests a new possible way to derive a nonlinear energy equation – by using vector form of the first law of thermodynamics. If previously obtained nonlinear Navier-Stokes equation is added to this nonlinear energy equation, a system of nonlinear equations could be obtained to correctly describe theory and practice of convective heat exchange, introducing completely new methods for calculating convective heat exchange (without using traditional heat transfer coefficients and laws of cooling).

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