ISSN 1561-2430 (Print)
ISSN 2524-2415 (Online)
UDC 536.23
https://doi.org/10.29235/1561-2430-2021-57-1-77-84

Received 23.12.2020
Поступила в редакцию 23.12.2020

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HEAT TRANSFER PROCESSES IN THE GAS PLACED INTO A NEWTONIAN GRAVITATION FIELD

Abstract. In this paper, using the theoretical and numerical investigation of molecular motion, we study heat transfer processes in the gas placed in a Newtonian gravitational field. The influence of gravity on the heat conductivity of the gas is analyzed. The gravity considered is more than 100 000 times higher than that of the Earth. The main differences of the gas heat conductivity under such high gravity from the one detected under normal gravity are demonstrated and explained. It is shown how the thermal equilibrium for the heat conductivity of the gas depends on gravity and the type of gas. The difference between natural gravity and the centrifugal force is discussed. It is shown how the gas density influences the thermal equilibrium for the heat conductivity under a strong centrifugal force. The convective heat transfer in the gas placed into a gravitational or centrifugal field is analyzed. It is shown that the thermal equilibrium of the convective heat transfer under intensive gravity is not the same as under normal gravity. The horizontal convection mechanism is discussed. A technical way of the realization of gravity thermal effects in the gas is represented. All necessary parameters of the experimental setup are given.

Keywords: heat transfer, molecular motion, thermal equlibrium, centrifugal gravity

For citation. Saverchenko V. I. Heat transfer processes in the gas placed into a Newtonian gravitation field. *Vestsi Natsyianal'nai akademii navuk Belarusi. Seryia fizika-matematychnykh navuk = Proceedings of the National Academy of Sciences of Belarus. Physics and Mathematics series*, 2021, vol. 57, no. 1, pp. 77–84 (in Russian). https://doi.org/10.29235/1561-2430-2021-57-1-77-84

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ТЕПЛОПЕРЕНОС В ГАЗАХ, НАХОДЯЩИХСЯ В НЬЮТОНОВСКОМ ГРАВИТАЦИОННОМ ПОЛЕ

Аннотация. Данная работа посвящена изучению механизмов теплопереноса в газах, помещенных в ньютоновское гравитационное поле. Исследования проводились при помощи теоретического анализа, а также численного моделирования теплового движения молекул газа в условиях гравитации свыше 100 000 g. Представлены основные отличия теплопроводности газа в гравитационном поле от теплопроводности газа при отсутствии гравитации. Показано, как тепловое равновесие, обеспечиваемое теплопроводностью газа, зависит от гравитации и разновидности газа. Исследования проводились не только для естественной, но и для искусственной гравитации, создаваемой центрифугой. Выявлено, как тепловое равновесие, обеспечиваемое теплопроводностью газа, зависит от плотности газа в центрифуге. Описаны паразитные эффекты, в том числе теплообмен излучением. Объяснены отличия конвективного теплопереноса при достаточно высокой гравитации от конвективного теплопереноса в условиях земной гравитации. Рассчитаны параметры теплового равновесия, которое обеспечивается конвекцией в газе, находящемся в гравитационном поле. Объяснен механизм горизонтальной конвекции. Предложен способ технической реализации тепловых эффектов, возникающих в газе при гравитации свыше 100 000 g. Даны необходимые технические параметры экспериментального стенда. Детально описана его конструкция.

Ключевые слова: теплоперенос в газе, тепловое движение молекул, тепловое равновесие, центробежная сила

Для цитирования. Саверченко, В. И. Теплоперенос в газах, находящихся в ньютоновском гравитационном поле / В. И. Саверченко // Вес. Нац. акад. навук Беларусі. Сер. фіз.-мат. навук. – 2021. – Т. 57, № 1. – С. 77–84. https://doi.org/10.29235/1561-2430-2021-57-1-77-84

Introduction. It is well known that heat is the energy of molecular motion. Therefore, it is interesting to understand how changes of molecular motion can affect heat processes. For example, gravity can change the trajectories of molecular motion in the gas. Thus, this paper is devoted to the analysis of the influence of gravity on the heat transfer in the gas.

It is shown [1] that diffusion in gases placed into a high gravitation field leads to decreasing the entropy. In other words, while under weak gravity the diffusion tends to mix the gases, under strong gravity the diffusion splits the gas into components: a heavy gas appears at the bottom and a light gas appears at the top. Therefore, the entropy of the system decreases. This factor is widely used in uranium enrichment [2]. The fact that transfer processes ignore the law of increasing entropy in gases [3] when they are placed into a gravitational field is the most interesting feature.

Although diffusion in gases placed into a gravitational field is well studied, the heat transfer in this case is unclear. This situation is due to the virtual lack of interest from the industry. However, the issue of the heat transfer in the gases placed into a strong gravitation field has a significant fundamental meaning. It can be used in studying stars formation mechanisms [4] and heat processes inside the stars. Some results of this study can be used to analyze the mechanism of the heat death of the Universe [5].

Gravitational shift of the thermal equilibrium for the gas heat conductivity. When we throw up a stone it slows down with the height increasing. Independently of the flight angle, the kinetic energy of the stone decreases proportionally to the increase of the potential energy. When we throw down the stone from the roof of a house it accelerates with the height decreasing. This is a result of the law of energy conservation. This study is based on the assumption that the law of energy conservation will be valid for moving gas molecules. So, when the molecule falls down in a gravitational field, it accelerates. When the molecule goes up, its speed decreases.

To exclude quantum effects, we consider the xenon gas. As long as the molecular diameter of xenon is 4.4Å, we consider its molecules as classical objects.

It is well known [6] that the temperature is determined by the intensity of the molecular motion. For example, the heat energy of a monatomic gas is the total kinetic energy of its moving molecules. The temperature of a monatomic gas is determined by the average energy of the linear motion of the molecules of this gas by equation (1). So, if a metal plate is placed into the gas, then its molecules attack this plate with the average energy determined by equation (1), where T is the gas temperature. It is well known [6] that if the temperature of the plate is higher than that of the gas, the heat energy flows from the plate to the gas. If the temperature of the plate is lower than that of the gas, the heat energy flows from the gas to the plate. So if gas molecules attack the plate with the average energy higher than $<E_k>$ from equation (1) (T is the temperature of the plate), the heat energy transfers from the gas to the plate. This means that the average energy of the gas molecules before interaction with the plate is higher than after interaction with the plate.

$$<E_k>=\frac{3}{2}kT, \quad (1)$$

where $<E_k>$ is the average kinetic energy of gas molecules; k is the Boltzmann constant; and T is the gas temperature.

It is important that the surface of the plate doesn't "know" the temperature of the surrounding gas. The plate "knows" only the energies with which gas molecules attack this plate. It is established in [7] that the angles of attack do not play any role either. Therefore, when a meteorite moves through a rarified atmosphere, it is heated to high temperatures by a cold rarified gas. The meteorite surface accepts the fast direct motion of the molecules of a cold gas exactly like the chaotic heat motion of a very hot gas.

Let us consider two infinite horizontal parallel metal plates and rarified xenon between them (see Fig. 1). The system is placed into zero gravity. As long as xenon is rarified, the gas molecules do not interact one with other. They interact only with the plates. After interaction with the top plate the gas molecule always interacts with the bottom plate. After interaction with the bottom plate the gas molecule interacts with the top plate again. For zero energy exchange between the gas and the top or bottom plate it is necessary that the average energy of the gas molecules before interaction to be equal $<E_k>$ from equation (1), where T is the temperature of the plate. In this case the average energy of the molecules after interaction will be equal to the average energy of these molecules before interaction. In zero gravity the average energy of the molecules after interaction with the top plate is equal to the average energy of these molecules before interaction with the bottom plate. This means that for zero heat exchange the average energies of the molecules before and after interaction with the top and bottom plates must be equal. So the temperatures of the plates must be equal in absence of heat exchange. It is well known (6) that this conclusion is correct.

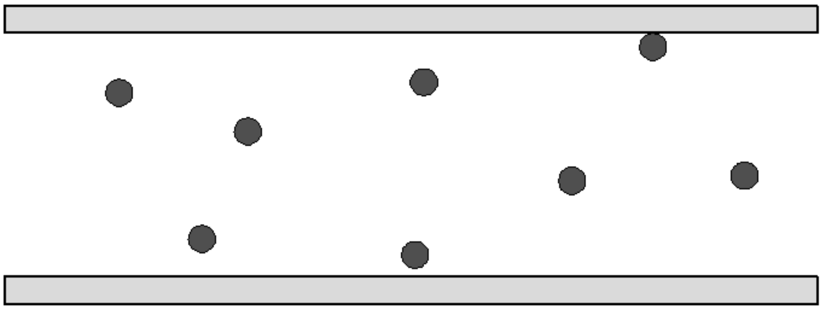

Fig. 1. Xenon molecules between two horizontal metal plates

Now let us consider the system (fig. 1) placed into a gravitational field. For zero energy exchange between the gas and the top or bottom plate it is necessary that the average energy of the gas molecules before interaction equals $\langle E_k \rangle$ from equation (1). The average energy of the molecules after interaction with any plate is equal to the average energy of these molecules before interaction. When the molecules move from the top to the bottom plate, their average kinetic energy increases by decreasing the potential energy. When the molecules move from the bottom to the top plate, their average kinetic energy decreases. This means that for zero heat exchange the temperature of the bottom plate must be higher than the temperature of the top plate by ΔT_{gs} from equation (2).

$$\Delta T_{gs} = \frac{2mgh}{3k}, \tag{2}$$

where m is the mass of the xenon molecule, which is equal to $2{,}2 \cdot 10^{-25}$ kg; h is the distance between the plates, m; g is gravity, m/s^2; k is the Boltzmann constant, which is equal to $1{,}38 \cdot 10^{-23}$ J/K; ΔT_{gs} is the temperature difference between the plates.

The mechanism of heat transfer provided by the motion and interaction of molecules is heat conductivity [6]. Thus, ΔT_{gs} is the gravitational shift of the thermal equilibrium for the heat conductivity mechanism.

The most extraordinary feature of the gravitational shift is that the equilibrium state is achieved when the temperatures of the plates are different. In the most common processes the equilibrium state is when all parts of the system have the same temperature. There are some exceptions [8, 9].

Radiative heat transfer. In spite of its simplicity the gravitational shift of the thermal equilibrium effect is difficult for detecting. The reason for this is the following. While the gravitational shift effect tries to establish the temperature difference between the plates, other mechanisms of heat transfer try to make the temperatures of the plates equal. So it is necessary to provide such conditions that the gravitational shift effect becomes stronger than all other mechanisms of heat transfer. These other mechanisms of heat transfer are the radiation and heat conductivity of the construction separating the plates. When we use a centrifuge to provide gravitation, we must also take into account the heating of the moving parts by friction.

Although the friction and heat conductivity of the construction can be diminished by technical ways, it is impossible to avoid the radiation heat transfer between the plates. It is because there are no absolutely specular materials for infrared rays. This, gravity must be so strong that the gravitational shift of the thermal equilibrium can take place in a very thin gas layer. The gas layer must be thin enough for the heat conductivity of the layer to be greater than the radiation heat transfer. It is due to the gravitational shift effect being provided by the heat conductivity mechanism. We know that for a thinner layer the heat conduction is stronger [6].

As long as the equilibrium is achieved when the top plate is colder than the bottom plate by ΔT_{gs} the heat flux per square meter is equal to

$$Q = \frac{\lambda \cdot \left(T_t + \Delta T_{gs} - T_b\right)}{h}. \tag{3}$$

According to [10], the radiation heat flux per square meter between the plates equals to

$$Q = \varepsilon_n C_0 \left[\left(\frac{T_b}{100} \right)^4 - \left(\frac{T_t}{100} \right)^4 \right], \tag{4}$$

where

$$\varepsilon_n = \frac{1}{\frac{1}{\varepsilon_t} + \frac{1}{\varepsilon_b} - 1},$$

$$C_0 = 5{,}67 \text{ W/m}^2 \cdot \text{K}.$$

When we compare (3) and (4), we find that h must be less than 1 cm. If we want ΔT_{gs} to be equal to 100 K, when h = 1cm, gravity must be 10^6 m/s^2, according to (2). This gravity is 100 000 times higher than that of the Earth. As will be shown later, for lighter gases like helium gravity must be stronger than for heavy gases like xenon. So we can say that it is possible to observe the gravitational shift of the thermal equilibrium only when gravity is more than 100 000 times higher than that of the Earth.

Gravitational shift of the thermal equilibrium of convection. We have just considered the gravitational shift of the thermal equilibrium in a rarefied gas. However, it is interesting to know if there would be such an effect in a normal gas. The gas is normal when the mean free pass of its molecules is much less than the distance between the plates but it is much longer than the diameter of the gas molecule. To understand the behavior of the gravitational shift effect in normal gases, computer numerical modeling was engaged. During simulation the average heat transfer between the plates was measured at different gas concentrations. The size of molecules was set large enough for them to interact one with another many times at a maximal concentration and almost not to interact at a minimal concentration. Numerical simulation did not show that the interaction of molecules eliminated the effect.

The chaotic motion and interaction of gas molecules can't eliminate the gravitational shift effect due to the following factors. The first is that rising molecules always slow down and falling molecules always speed up despite the direction of motion. The second is that when molecules interact one with another, their average kinetic energy remains the same [6].

Although convection in a rarified gas is impossibl,e it can appear in a normal gas. One can say that when the bottom is hotter than the top, convection will immediately occur and equalize the temperatures of the plates. However, it is not so because at a gravity of 10^6 m/s^2 even a 1 cm gas layer creates high hydrostatic pressure. When the gas rises up, it looses the pressure and thus expands and cools. So every adiabatic vertical flow of gas under gravity will create a temperature difference

$$\Delta T_{sc} = \frac{2mgh}{(i+2)k}, \tag{5}$$

where i is the number of degrees of freedom of the molecular motion.

The temperature difference ΔT_{sc} appears because the rising gas adiabatically expands and cools and the gas adiabatically shrinks and heats. So if ΔT_{gs} is the shift of the thermal equilibrium for the heat conductivity mechanism, ΔT_{sc} is the shift of the thermal equilibrium for convection.

Comparison of (2) and (5) shows that for xenon ΔT_{sc} is almost twice smaller than ΔT_{gs}. This means that convection will not disturb the heat conductivity until the temperature difference ΔT_{sc} is achieved. So for the rarified gas the equilibrium temperature difference will be ΔT_{gs}, and for the normal gas it will be ΔT_{sc}. The main difference between heat conductivity and the convection gravitational shift is that heat conductivity acts when the temperature difference achieves a state of equilibrium, but convection acts only when the temperature difference is larger than the equilibrium.

Different gases. Molecules of a polyatomic gas have twice more kinetic energy than monatomic gas molecules at the same temperature [6]. But the gravitational energy increment of the molecule, when it moves from the top plate to the bottom one, depends only on the molecular mass. So, the relative energy increment for a monatomic molecule is twice larger than that for a polyatomic molecule. That is why we can rewrite equation (2) for the polyatomic gas as

$$\Delta T_{gs} = \frac{2mgh}{ik}. \tag{6}$$

Besides the temperature difference of the gravitational shift ΔT_{gs}, it is important to know the heat flux Q of the heat conductivity. It is known that Q is proportional to the heat conductivity λ of the gas. It is also known [6] that the heat conductivity λ is proportional to the relation of the number of degrees of freedom i to the effective interaction cross section s. If we suppose that s is proportional to $m^{2/3}$, we find that

$$\lambda \propto i \cdot m^{-2/3}. \tag{7}$$

If the temperatures of the top and bottom plates are equal, then the conductive heat flux is proportional to $\lambda \cdot \Delta T_{gs}$. Taking into account (6), we find that

$$Q \propto m^{1/3}. \tag{8}$$

The power of the conductive heat flux Q does not depend on the distance between the plates h. It is owing to the fact that with increasing h not only ΔT_{gs} increases, but the thermal resistance of the gas layer h/λ also increases.

Looking on (6), we understand that the temperature difference of the gravitational shift ΔT_{gs} is maximal for heavy monatomic gases. Equation (8) shows that the heat power of the heat conductivity caused by the gravitational shift of the thermal equilibrium is maximal for heavy gases. Thus xenon is the most appropriate gas for our studies.

Artificial gravity. As it was said before, gravity must be 100 000 times stronger than that of the Earth for detecting the gravitational shift of the thermal equilibrium. Such high gravity is common in the Universe, but on the Earth this gravity can be only artificial. To create artificial gravity for a single molecule we can charge this molecule and place it into an electric field [9]. Still, for many molecules this method would not simulate gravity because of the charged molecules repelling one from another. So, a centrifuge is necessary to create gravity.

However the centrifugal force is not always the same as compared with gravity. When we want to create gravity by a centrifuge it is necessary for the centrifugal force to be much higher than the Coriolis force (9).

$$\begin{cases} g = \dfrac{V_c^{\,2}}{R}, \\ a_x = \dfrac{2gV_y}{V_c}, \\ a_y = \dfrac{-2gV_x}{V_c}, \end{cases} \tag{9}$$

where g is centrifugal gravity; V_x is the horizontal speed of the molecule; V_y is the vertical speed of the molecule; a_x is the horizontal acceleration by the Coriolis force; a_y is the vertical acceleration by the Coriolis force; and V_c is the circular speed of the centrifuge.

Equation (9) shows that when the circular speed of the centrifuge is much higher than the speed of molecules we have only gravity. In this case the behavior of molecules in the centrifuge will be the same as under real gravity. The maximal circular speed [11] that the centrifuge can sustain is

$$V_{\max} = Z\sqrt{\frac{\sigma}{\rho}}, \tag{10}$$

where σ is the tensile strength; ρ is the density; and Z is a constant.

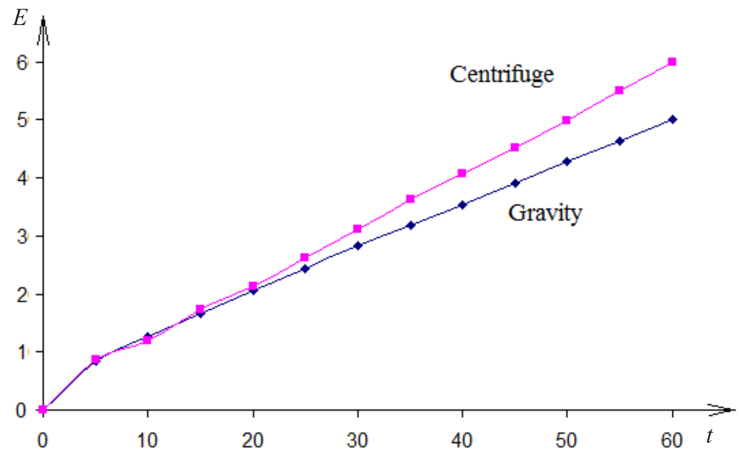

Fig. 2. Molecular trajectories

The constant Z in equation (10) equals 1 for a tube centrifuge and 1.4 for a disc centrifuge. For the creation of a gravitational shift a tube centrifuge is necessary. If we build a centrifuge from metal and give it twice the margin of safety, the maximal circular speed of the centrifuge will be V_{max} ~ 200 m/s. Xenon molecules have the same average speed at room temperature. So we must take into account the Coriolis force. The condition of real gravity can be created only by a boron fiber centrifuge. Thus it is necessary to understand how the Coriolis force affects the gravitational shift.

A numerical simulation of the molecular motion was employed to understand how the Coriolis force affects the gravitational shift. Figure 2 shows the growth of the thermal energy of the bottom plate in the case of pure gravity and in the case of the centrifugal gravity with the same magnitude.

In Fig. 2, the circular velocity of the centrifuge is equal to the average molecular velocity. Heat is illustrated in relative units. The gas is rarified. The number of molecules is 500. It is seen that there is no large difference between gravity and the centrifuge as to the gravitational shift.

Realization of the effect. For the realization of the gravitational shift effect of the thermal equilibrium it is necessary to create gravity being 100 000 times stronger than that of the Earth. Besides that, the construction must provide conditions when the internal radiation heat transfer and the heat conductivity of the construction are less strong than the heat conductivity of the gas. Finally, the setup must give us a possibility to detect the effect. The best way to detect the gravitational shift is to convert the temperature difference ΔT_{gs} to electricity. To obtain the gravitational shift and convert the resulting temperature difference into electricity a special setup is necessary. Figure 3 shows a schematic view of such a setup in cross section.

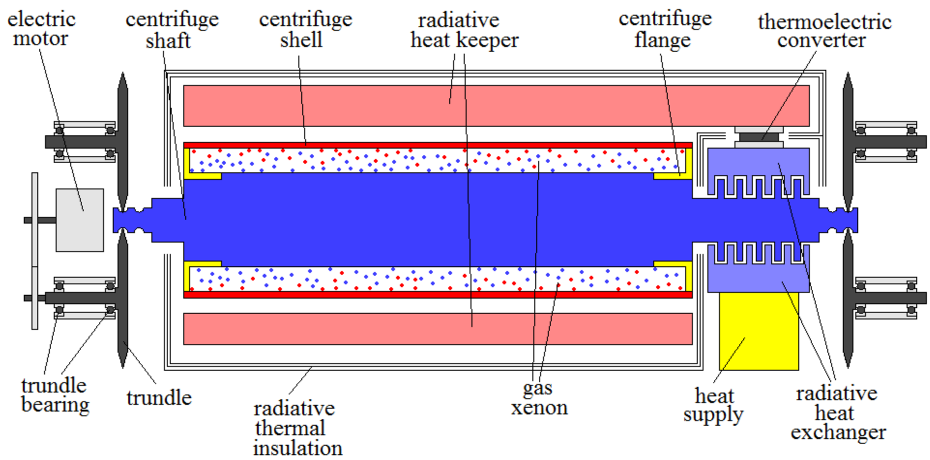

Fig. 3. Schematic section of the setup without background

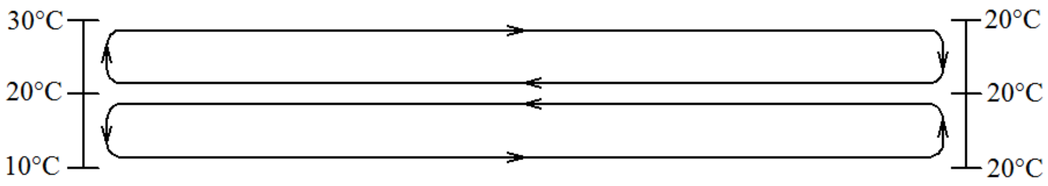

Fig. 4. Schematic illustration of horizontal convection

A centrifuge is the main part of the setup. It creates the necessary gravity in which the temperature difference appears due to the gravitational shift effect. The centrifuge consists of a shaft, flanges, and a shell. A space between shaft and shell is filled by xenon, in which a gravitational shift takes place. The external surface of the shaft and the internal surface of the shell are polished black, as it is necessary to minimize the radiation heat exchange between shaft and shell. The flanges are very thin and made from plastic with low heat conductivity, as it is necessary to minimize the conductive heat exchange between shaft and shell. This heat exchange, as well as the radiative heat exchange, reduces the gravitational shift effect. The external surface of the shell and the internal surface of the radiative heat keeper are black to maximize the radiation heat transfer.

When the centrifuge rotates, a gravitational shift of the thermal equilibrium appears in xenon. This shift creates a temperature difference between the shaft of the centrifuge and its shell. The radiative heat keeper and the radiative heat exchanger are used to take off the temperature difference from the rotating centrifuge without mechanical contact with it. Mechanical contact with the static parts is inadmissible for the centrifuge to rotate without friction. The radiative heat exchanger and the radiative heat keeper take off the temperature difference from the centrifuge and transmit this difference to the thermoelectric converter [8]. The thermoelectric converter converts the temperature difference to electricity.

When some part of the heat energy is converted to electricity in the thermoelectric converter, the system becomes colder. To avoid overcooling, the setup is equipped by a heat supply. The heat supply gives heat for the system from the outside.

The centrifuge is set on a special suspension. This suspension consists of eight trundles, only four of which are illustrated in Fig.3. The suspension is necessary for the centrifuge to rotate quickly with minimal friction. To avoid viscous friction, the system is placed into a high vacuum of $\sim 10^{-6}$ Pa. Vacuum is also need to diminish the parasite heat transfer.

Horizontal convection. During the analysis of the heat exchange between the flanges of the centrifuge (see Fig. 3) and xenon one interesting mechanism of the heat transfer was found. This mechanism can not appear under natural Earth gravity. The mechanism is horizontal convection. This mechanism is schematically shown in Fig. 4.

The picture in Fig.4 is distorted because the real vertical size of loop flows is about 1 mm while the horizontal size is more than 100 mm. That is why the convection is called horizontal. On the right side of Fig. 4 we see the flange of the centrifuge with a uniform temperature. On the left side we see an imaginary wall with the temperature arrangement caused by the gravitational shift of the thermal equilibrium. Figure 4 shows that if the flange has a uniform temperature it eliminates the gravitational shift. That is why the flanges must be very thin and there must be a high vacuum outside the flanges.

Horizontal convection is impossible under natural gravity because of the weak Archimedes force. Under natural gravity the viscosity of the gas inhibits the flow motion, and the heat conductivity of the gas equalizes the temperature of the flows. This mechanism can also be used for the explanation of parasite flows in a fast moving plasma [12].

Conclusion. The heat transfer in gases placed into a gravitational field is not the same as under zero gravity. The shifted convection, gravitational shift of the thermal equilibrium, and horizontal convection can appear only when gravity is very strong.

The effect of the gravitational shift of the thermal equilibrium for heat conductivity can take place in different gases. Convection effects appear only in normal gases. The temperature difference of the heat conductivity gravitational shift is always higher than the gravitational shift of the thermal equilibrium for convection. Conductive heat transfer occurs only when the temperature difference is not the same as in the equilibrium. Convection occurs only when the temperature difference is higher than that in the equilibrium.

The temperature difference caused by the gravitational shift for heat conductivity is maximal for heavy monatomic gases. The heat flux caused by the gravitational shift for heat conductivity is maximal for heavy gases. Xenon is the most appropriate gas for studies of the gravitational shift effect.

The centrifugal force is not always the same as gravity. Numerical simulation of the molecular motion shows that the gravitational shift can arise in the centrifuge as soon as under real gravity.

It is shown that the creation conditions for the gravitational shift are technically possible. The scheme of the setup is suggested. The main technical difficulties in the creation of the gravitational shift are a high vacuum (~10^{-6} Pa) and a high frequency rotation of the centrifuge (~150 000 1/min).

This study is based on numerous assumptions and simplifications. The real mechanism of molecular motion and interactions is not clear enough to rely on some numerical estimations. Thus the experimental verification of all the results is necessary.

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