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Instrumentação para Ensino – F 809

RADIÔMETRO DE CROOKES III

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Introdução

O radiômetro é um instrumento capaz de medir radiação. Ao incidir sobre as palhetas do radiômetro, a luz faz com que se inicie um movimento de rotação das palhetas em torno do eixo da haste que o sustenta (figura 1).

Quando observou pela primeira vez o movimento, Maxwell imaginou estar observando um experimento que comprovava sua previsão a respeito da pressão de radiação que uma onda eletromagnética exerce sobre a matéria. Ledo engano, pois o movimento ocorria no sentido inverso ao previsto por sua teoria. Até os dias de hoje, acredita-se que o fenômeno que ocorre tem natureza termodinâmica, sendo o movimento gerado por correntes de convecção do meio geradas pelo aquecimento desigual das faces das palhetas.

A solução correta para o fenômeno foi dada qualitativamente por Osborne Reynolds. Em 1879 Reynolds submeteu um artigo à Royal Society no qual considerava o que chamou de “transpiração térmica” e também discutiu a teoria do radiômetro. Ele chamou de “transpiração térmica” o fluxo de gás através de palhetas porosas caudado pela diferença de pressão entre os lados da palheta. Se o gás está inicialmente à mesma pressão dos dois lados, há um fluxo de gás do lado mais frio para o lado mais quente, resultando em uma pressão maior do lado quente se as palhetas não se movessem. O equilíbrio é alcançado quando a razão entre as pressões de cada lado é a raiz quadrada da razão das temperaturas absolutas. Este é um efeito anti-intuitivo devido a forças tangenciais entre as moléculas do gás e os extremos dos poros nas palhetas. O efeito dessas forças termomoleculares é muito similar aos efeitos termomecânicos do hélio líquido superfluido. O líquido, que perde toda sua viscosidade, “escala” os lados do recipiente em direção a uma região mais quente. Se um capilar fino é posto no superfluido, ele sobe pelo tubo a tal velocidade que produz um efeito de fonte na outra extremidade.

As palhetas do radiômetro não são porosas. Para explicar o radiômetro, entretanto, precisamos nos ater não nas faces das palhetas, mas nas suas bordas. As moléculas mais velozes do lado quente atingem as bordas obliquamente e transferem uma força maior que as do lado mais frio. Novamente estas são as mesmas forças termomoleculares responsáveis pela “transpiração térmica”. O efeito também é conhecido como “rastejo térmico”, por fazer com que o gás “rasteje” pela superfície onde haja gradiente de temperatura. O movimento total das palhetas devido às forças tangenciais sobre suas bordas é no sentido do gás mais quente para o mais frio, com o gás fluindo na direção oposta. O comportamento é como se tivesse uma força maior no lado preto das palhetas, mas a explicação deve ser dada em termos do que acontece nas faces das palhetas, mas nas proximidades de suas bordas.

Descrição do Experimento

O radiômetro é formado por um conjunto de quatro palhetas, dispostas em ângulos de 90° entre si, sendo que cada palheta tem uma face preta e outra prateada, montadas sobre uma base. Essa base, por sua vez, é colocada sobre uma haste com uma ponta muito fina. Todo esse sistema é montado em uma câmara de vácuo (figura 1).

Figura 1 - Radiômetro vendido no comércio.

Para os testes iniciais, utilizei o equipamento montado pelo aluno Wagner Soares [2], em novembro de 2005 nesta mesma disciplina (figura 2), e no fim eu fechei o radiômetro em um bulbo de vidro.

Figura 2 - Montagem realizada em outro semestre na mesma disciplina, com as palhetas de alumínio confeccionadas por mim.

Para a confecção das palhetas, utilizei chapas de alumínio de latas de cerveja, que passou pelo processo de preparação descrito no relatório parcial, sendo o lado prateado das palhetas o próprio metal e o lado preto feito com deposição de carbono amorfo (fuligem de vela) (figuras 2, 3 e 4).

Figura 3 - Sistema montado sobre haste de testes

Figura 4 - Detalhe do sistema base-palheta. O paquímetro nos dá uma idéia das dimensões da peça.

Para que a base não caia da haste caso o radiômetro seja tombado, montei a base em um apoio mais profundo (figuras 3 e 4), como indicado no relatório parcial, de tal maneira que o curso da haste dentro do apoio seja maior que o curso das palhetas até a parede interna do bulbo, garantindo que não seja possível que o sistema seja desmontado por acidente.

Com o auxílio da oficina de vidraria do IFGW foi possível a confecção do bulbo e a montagem do aparato para ser atrelado à bomba de vácuo do Laboratório de Ensino de Vácuo e Criogenia (figura 5).

Figura 5 - Bulbo, base e haste, peças para a montagem do radiômetro. Trabalho realizado na oficina de vidraria do IFGW.

Depois de um dia inteiro em vácuo, para tirar possíveis impurezas que atrapalham o vácuo, colocamos o sistema na pressão ótima com inserção de argônio e selamos o sistema.

Experimentos Realizados

Além dos experimentos relatados no relatório parcial, determinei também a pressão ótima para o sistema de alumínio dentro do bulbo de vidro através dos dados apresentados na tabela 1.

Também estimei uma aproximação para a influência da pressão de radiação no movimento das palhetas, dado que este não é o fenômeno principal na rotação das palhetas. Para isso, inicialmente medi a massa da peça da figura 2, que representa o sistema base-palhetas. Com a massa da peça, determinei o momento de inércia do sistema. Com o sistema a uma velocidade angular inicial conhecida, medi o tempo que o sistema demora a parar. Com esse tempo e o momento de inércia, pude calcular o torque de atrito do sistema. Com o espectro de emissão do Sol (obtido em um experimento realizado por mim na disciplina F 640 – Vácuo e Criogenia) e a área das palhetas, pude calcular o momento transferido na forma de pressão de radiação e comparar com o momento transferido termodinamicamente, principal responsável pelo movimento do radiômetro.

Agradecimentos

Gostaria de agradecer a dedicação dos funcionários Ademir Carlos Camillo, da oficina de vidraria do IFGW, e Renato, técnico do Laboratório de Ensino de Vácuo e Criogenia, também do IFGW. Sem suas colaborações não seria possível a realização deste trabalho.

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[2] Soares, W. “Relatório Final de F 809 – Radiômetro de Crookes III”, IFGW, Unicamp, Novembro de 2005

[3] http://en.wikipedia.org/wiki/Light_mill (Apêndice B)

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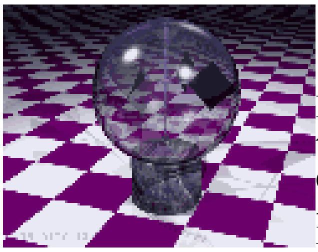

How does a light-mill work?

In 1873, while investigating infrared radiation and the element thallium, the eminent Victorian experimenter Sir William Crookes developed a special kind of radiometer, an instrument for measuring radiant energy of heat and light. Crookes's Radiometer is today marketed as a conversation piece called a light-mill or solar engine. It consists of four vanes each of which is blackened on one side and silvered on the other. These are attached to the arms of a rotor which is balanced on a vertical support in such a way that it can turn with very little friction. The mechanism is encased inside a clear glass bulb which has been pumped out to a high, but not perfect, vacuum.

When sunlight falls on the light-mill the vanes turn with the black surfaces apparently being pushed away by the light. Crookes at first believed this demonstrated that light radiation pressure on the black vanes was turning it round just like water in a water mill. His paper reporting the device was refereed by James Clerk Maxwell who accepted the explanation Crookes gave. It seems that Maxwell was delighted to see a demonstration of the effect of radiation pressure as predicted by his theory of electromagnetism. But there is a problem with this explanation. Light falling on the black side should be absorbed, while light falling on the silver side of the vanes should be reflected. The net result is that there is twice as much radiation pressure on the metal side as on the black. In that case the mill is turning the wrong way.

When this was realised other explanations for the *radiometer effect* were sought and some of the ones that people came up with are still mistakenly quoted as the correct one. It was clear that the black side would absorb heat from infrared radiation more than the silver side. This would cause the rarefied gas to be heated on the black side. The obvious explanation in that case, is that the pressure of the gas on the darker size increases with its temperature creating a higher force on that side of the vane. This force would push the rotor round. Maxwell analysed this theory carefully presumably being wary about making a second mistake. He discovered that in fact the warmer gas would simply expand in such a way that there would be no net force from this effect, just a steady flow of heat across the vanes. So it is wrong, but even the Encyclopaedia Britannica gives this false explanation today. As a variation on this theme, it is sometimes said that the motion of the hot molecules on the black side of the vane provide the push. Again this is not correct and could only work if the mean free path between molecular collisions were as large as the container, but in fact it is typically less than a millimetre.

To understand why these common explanations are wrong think first of a simpler set-up in which a tube of gas is kept hot at one end and cool at the other. If the gas behaves according to the ideal gas laws with isotropic pressure, it will settle into a steady state with a temperature gradient along the tube. The pressure will be the same throughout otherwise net forces would disturb the gas. The density would vary inversely to temperature along the tube. There will be a flow of heat from the hot end to the other but the force on both ends will be the same because the pressure is equal. Any mechanism you might conjecture that would give a stronger force on the hot end than on the cool end with no tangential forces along the length of the tube cannot be correct since otherwise there would be a net force on the tube with no opposite reaction. The radiometer is a little more complex but the same principle should apply. No net force can be generated by normal forces on the faces of the vanes because pressure would quickly equalise to a steady state with just a flow of heat through the gas.

Another blind alley was the theory that the heat vaporised gases dissolved in the black coating which then leaked out. This outgassing would propel the vanes round. Actually, such an effect does exist but it is not the real explanation as can be demonstrated by cooling the radiometer. It is found that the rotor then turns the other way. Furthermore, if the gas is pumped out to make a much higher vacuum, the vanes stop turning. This suggests that the rarefied gas is involved in the effect. For similar reasons, the theory that the rotation is propelled by electrons dislodged by the photoelectric effect is also ruled out. One last incorrect explanation which is sometimes given is that the heating sets up convection currents with a horizontal component that turns the vanes. Sorry, wrong again. The effect cannot be explained this way.

The correct solution to the problem was provided qualitatively by Osborne Reynolds, better remembered for the "Reynolds number". Early in 1879 Reynolds submitted a paper to the Royal Society in which he considered what he called "thermal transpiration", and also discussed the theory of the radiometer. By "thermal transpiration" Reynolds meant the flow of gas through porous plates caused by a temperature difference on the two sides of the plates. If the gas is initially at the same pressure on the two sides, there is a flow of gas from the colder to the hotter side, resulting in a higher pressure on the hotter side if the plates cannot move. Equilibrium is reached when the ratio of pressures on either side is the square root of the ratio of absolute temperatures. This is a counterintuitive effect due to tangential forces between the gas molecules and the sides of the narrow pores in the plates. The effect of these thermomolecular forces is very similar to the thermomechanical effects of superfluid liquid helium. The liquid, which lacks all viscosity, will climb the sides of its container towards a warmer region. If a thin capillary is dipped into the superfluid it flows up the tube at such speed that a fountain effect is produced at the other end.

The vanes of a radiometer are not porous. To explain the radiometer, therefore, one must focus attention not on the faces of the vanes, but on their edges. The faster molecules from the warmer side strike the edges obliquely and impart a higher force than the colder molecules. Again these are the same thermomolecular forces that are responsible for thermal transpiration. The effect is also known as thermal creep since it causes gases to creep along a surface where there is a temperature gradient. The net movement of the vane due to the tangential forces around the edges is away from the warmer gas and towards the cooler gas with the gas passing round the edge in the opposite direction. The behaviour is just as if there were a greater force on the blackened side of the vane (which as Maxwell showed is not the case), but the explanation must be in terms of what happens not at the faces of the vanes but near their edges.

Maxwell refereed Reynolds's paper, and so became aware of Reynolds's suggestion. Maxwell at once made a detailed mathematical analysis of the problem, and submitted his paper, "On stresses in rarefied gases arising from inequalities of temperature", for publication in the Philosophical Transactions; it appeared in 1879, shortly before his death. The paper gave due credit to Reynolds's suggestion that the effect is at the edges of the vanes, but criticised Reynolds's mathematical treatment. Reynolds's paper had not yet appeared (it was published in 1881), and Reynolds was incensed by the fact that Maxwell's paper had not only appeared first, but had criticised his unpublished work! Reynolds wanted his protest to be published by the Royal Society, but after Maxwell's death this was thought to be inappropriate.

By the way. It *is* possible to measure radiation pressure using a more refined apparatus. To make it work you have to use a much better vacuum, suspend the vanes from fine fibers and coat the vanes with an inert glass to prevent out-gassing. When you succeed the vanes are deflected the other way as predicted by Maxwell. The experiment is very difficult but was first done successfully in 1901 by Pyotr Lebedev and also by Eenest Nichols and Gordon Hull.

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Crookes radiometer

From Wikipedia, the free encyclopedia

(Redirected from Light mill)

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The **Crookes radiometer**, also known as the **light mill** or **solar engine**, consists of an airtight glass bulb, containing a partial vacuum. Inside are a set of vanes which are mounted on a spindle. The vanes rotate when exposed to light. The reason for the rotation has been the cause of much scientific debate.

It was invented in 1873 by the chemist Sir William Crookes as the by-product of some chemical research. In the course of very accurate quantitative chemical work, he was weighing samples in a partially evacuated chamber to reduce the effect of air currents, and noticed the weighings were disturbed when sunlight shone on the balance. Investigating this effect, he created the device named after him. It is still manufactured and sold to this day as a curiosity item.

Crookes Radiometer

[edit] General description

The radiometer is made from a glass bulb from which much of the air has been removed to form a partial vacuum. Inside the bulb, on a low friction spindle, is a rotor with several (usually four) vertical lightweight metal vanes spaced equally around the axis. The vanes are polished or white on one side, black on the other. When exposed to sunlight, artificial light, or infrared radiation (even the heat of a hand nearby can be enough), the vanes turn with no apparent motive power, the dark sides retreating from the radiation source and the light sides advancing. Cooling the radiometer causes rotation in the opposite direction.

The effect begins to be seen at partial vacuum pressures of a few millimeters of mercury (torr) , reaches a peak at around 10^{-2} torr and has disappeared by the time the vacuum reaches 10^{-6} torr (see note 1). At these very high vacuums the effect of photon radiation pressure on the vanes can be observed in very sensitive apparatus (see Nichols radiometer) but this is insufficient to cause rotation.

Although it has the word-element "meter" in its title, a Crookes radiometer does not quantitatively measure anything by itself. A measurement of the speed of its rotation can, however, be obtained using a spinning slotted disk, which functions as a simple stroboscope. The light from an actual light strobe would distort the measurement.

Radiometers are now commonly sold worldwide as an interesting household novelty ornament, no batteries needed, just light to get the vanes to turn; strong light gets them spinning furiously. They come in various forms, as the one pictured, and are also to be found often used in science museums to illustrate the hidden power of light and heat.

[edit] Thermodynamic explanation

[edit] External radiant source motion

For any heat engine to turn, there must be a difference in temperature. In this case, the black side of the vane is hotter than the other side, as radiant energy from a light source warms the black side by black-body absorption faster than the silver or white side. The internal air molecules are "heated up" (i.e. experience an increase in their speed) when they touch the black side of the vane. The details of exactly how this moves the hotter side of the vane forward are given in the section below *Explanations for the force on the vanes*.

The internal temperature rises as the black vanes impart heat to the partial vacuum molecules, but they are cooled again when they touch the bulb's glass surface which is at ambient temperature. Heat loss through the glass keeps the internal bulb temperature steady so that the two sides of the vanes can develop a temperature difference. The white or silver side of the vanes are slightly warmer than the internal air temperature but cooler than the black side, as some heat conducts through the vane from the black side. The two sides of each vane must be thermally insulated to some degree so that the silver or white side does not immediately reach the temperature of the black side. If the vanes are made of metal, then the black or white paint can be the insulation. The glass stays much closer to ambient temperature than the temperature reached by the black side of the vanes. The higher external air pressure helps conduct heat away from the glass.

A strong vacuum inside the bulb does not permit motion because there are not enough air molecules to cause air currents to move the vanes and to transfer heat to the outside before both sides of each vane reach thermal equilibrium by heat conduction through the vane material. Higher inside pressure does not permit motion because the temperature differences are not enough to move the higher concentration of air. There is too much air resistance for "eddy currents" to occur. The slight air movement caused by the temperature difference is blocked by the higher pressure before the effects can "wrap around" to the other side.

[edit] Motion without external radiation

When heating the radiometer in the absence of a light source, it turns in the forward direction (i.e. the black sides trailing). You can place your hands around but not quite touching the glass and it will turn slowly or not at all, but if you touch the glass to warm it quickly, it will turn more noticeably. The directly heated glass gives off enough infrared radiation to turn the vanes, but if the hands are not touching the glass, the glass blocks much of the far-infrared radiation. Near-infrared and visible light more easily penetrate the glass.

If you cool the glass quickly in the absence of a strong light source by placing ice on the glass, it turns backwards (i.e. the silver sides are trailing). This demonstrates black-body radiation from the black sides of the vanes rather than black-body absorption. It turns backwards because the black sides give off more heat and cool more quickly than the other side.

The rotation lasts only as long as the temperature of the glass is increasing or decreasing fast enough to overcome the friction of the spindle and faster than the temperature conduction through the vanes can cause the two sides of the vanes to reach equal temperature.

[edit] Explanations for the force on the vanes

Over the years, there have been many attempts to explain how a Crookes radiometer works:

1. Crookes incorrectly suggested that the force was due to the pressure of light. This theory was originally supported by James Clerk Maxwell who had predicted this force. This explanation is still often seen in leaflets packaged with the device. The first experiment to disprove this theory was done by Arthur Schuster in 1876, who observed that there was a force on the glass bulb of the Crookes radiometer that was in the opposite direction to the rotation of the vanes. This showed that the force turning the vanes was generated inside the radiometer. If light pressure was the cause of the rotation, then the better the vacuum in the bulb, the less air resistance to movement, and the faster the vanes should spin. In 1901, with a better vacuum pump, Pyotr Lebedev showed that in fact, the radiometer only works when there is low pressure gas in the bulb, and the vanes stay motionless in a hard vacuum. Finally, if light pressure were the motive force, the radiometer would spin in the opposite direction as the photons on the shiny side being reflected would deposit more momentum than on the black side where the photons are absorbed. The actual pressure exerted by light is far too small to move these vanes but can be measured with devices such as the Nichols radiometer.

2. Another incorrect theory was that the heat on the dark side was causing the material to outgas, which pushed the radiometer around. This was effectively disproved by both Schuster's and Lebedev's experiments.

3. A partial explanation is that gas molecules hitting the warmer side of the vane will pick up some of the heat i.e. will bounce off the vane with increased speed. Giving the molecule this extra boost effectively means that a minute pressure is exerted on the vane. The imbalance of this effect between the warmer black side and the cooler silver side means the net pressure on the vane is equivalent to a push on the black side, and as a result the vanes spin round with the black side trailing. The problem with this idea is

that the faster moving molecules produce more force, they also do a better job of stopping other molecules from reaching the vane, so the force on the vane should be exactly the same — the greater temperature causes a decrease in local density which results in the same force on both sides. Years after this explanation was dismissed, Albert Einstein showed that the two pressures do not cancel out exactly at the edges of the vanes because of the temperature difference there. The force predicted by Einstein would be enough to move the vanes, but not fast enough.

4. The final piece of the puzzle, thermal transpiration, was theorized by Osborne Reynolds, but first published by James Clerk Maxwell in the last paper before his death in 1879. Reynolds found that if a porous plate is kept hotter on one side than the other, the interactions between gas molecules and the plates are such that gas will flow through from the cooler to the hotter side. The vanes of a typical Crookes radiometer are not porous, but the space past their edges behave like the pores in Reynolds's plate. On average, the gas molecules move from the cold side toward the hot side whenever the pressure ratio is less than the square root of the (absolute) temperature ratio. The pressure difference causes the vane to move cold (white) side forward.

Both Einstein's and Reynolds's forces appear to cause a Crookes radiometer to rotate, although it still isn't clear which one is stronger.

See also: photophoresis.

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