Entropy decreasing in a mechano-caloric effect of superfluid ^{4}He, and its application in energy generation

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Abstract. In this note, we point out that a case of mechano-caloric effect of superfluid ^{4}He actually establishes a temporary entropy-decreasing process, which was unnoticed in the past. We show that this process can be used to convert thermal energy from the environment to useful energy in principle, and therefore, the second law of thermodynamics is not a universal law.

Keywords: entropy-decreasing process, two-fluid model

The so-called mechano-caloric effect of superfluid ^{4}He was observed [1] shortly after the discovery of superfluidity [2]. A typical case of mechano-caloric effect discussed in textbooks [3] is schematically plotted in Fig. 1. In the process of (1)$\longrightarrow$(2)$\longrightarrow$(3) in Fig. 1, some superfluid helium passes through a narrow capillary and flows into the vessel at right side with a decreased temperature. This (1)$\longrightarrow$(2)$\longrightarrow$(3) process is actually an entropy-decreasing process. One could calculate the entropy of the system at (1), (2) and (3) for drawing such a conclusion. It can also be qualitatively argued in the following way: the entropy of system at (1) is roughly equal to the entropy of the system at (4). One can reach the state (3) from starting at the state (4) by gradually transferring heat from the superfluid helium at right vessel to the superfluid helium at left vessel. A small amount of heat transfer leads to a temperature decrease of liquid helium at right vessel and a temperature increase of liquid helium at left vessel, thus the temperature of liquid helium at right vessel is lower than the temperature of liquid helium at left vessel. Further heat transfer, by which one eventually reaches state (3), is a heat transfer from a lower temperature part to a higher temperature part and correspondingly the entropy decreases. Therefore, the entropy of system at state (3) is lower than at state (4) or at state (1), and the process of (1)$\longrightarrow$(2)$\longrightarrow$(3) should involve some entropy-decreasing

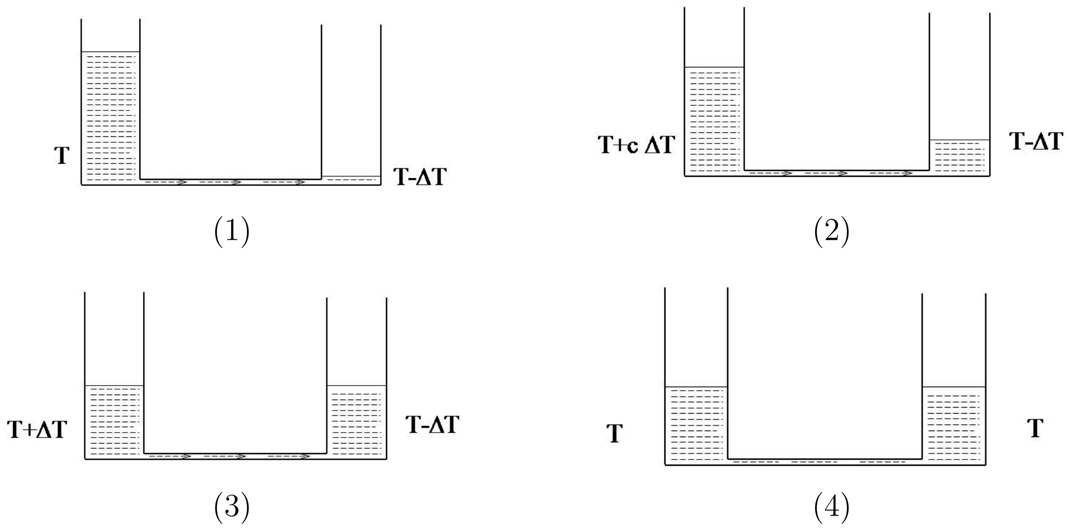

Figure 1: A schematic plot of a typical mechano-caloric effect of superfluid ^{4}He. The temperatures of liquid ^{4}He at both sides are denoted by combinations of T and ΔT (in a rough rather than accurate way). $0 < c < 1$.

process. The further temporal evolution of this mechano-caloric process involves that liquid helium flows back and forth between two vessels and that the system eventually reaches the state (4). Thus, the entropy-decreasing process in this mechano-caloric effect is temporary. A temporary entropy-decreasing process is unusual since it could imply a violation of the second law of thermodynamics.

Note that in the process of (1)$\longrightarrow$(2)$\longrightarrow$(3), the gravitational potential energy of liquid helium decreases. One might suggest that the decrease of entropy could be a result of work done to the system by gravitation. However, according to the second law of thermodynamics, any work done to a (thermally isolated) system has no way to cause a decrease of the total entropy of the system. One could also show that the change of gravitational potential energy in the process of (1)$\longrightarrow$(2)$\longrightarrow$(3) can be orders of magnitude smaller than the difference between the internal energy of the liquid helium at the left vessel (with a temperature of $T + \Delta T$) at (3) and the internal energy of liquid helium of the same amount but with a temperature of T, which suggests that the gravitational force can be excluded as a determinant factor for this unusual entropy-decreasing process.

It is of fundamental interest to clarify the microscopic mechanism behind this temporary entropy-decreasing process in the mechano-caloric effect of superfluid ^{4}He. So-called two-fluid model provides a phenomenological understanding of the mechano-caloric effect. However, the validity of two-fluid model is not guaranteed. There are several issues concerning two-fluid models. First, an experiment on rotating superfluid ^{4}He in a bucket [6] demonstrates a phenomenon which completely contradicts two-fluid model. Second, two-fluid model postulates that the fluid helium passes through the capillary is superfluid component with zero entropy. This zero entropy state is also a zero temperature state without any thermal excitation energy, since all thermal excitations (phonons and rotons) belong to the normal component which 'sticks' with the inner wall of the capillary. This postulation of a superflow state with zero entropy and zero temperature violates the third law of thermodynamics, which affirms that zero temperature state of a matter can't be reached in a finite steps. The issues surrounding two-fluid model suggest that its reliability is questionable and that it needs to be tested. Recently a developed microscopic theory of superfluidity (in terms of quantum many-body states and jumps among the states) (see, e.g., [7, 8, 9]) illustrates the natural quantum mechanism behind the entropy-decreasing process [4, 5]. Moreover, one can construct a steady entropy-decreasing process involving ^{4}He superflows and further can build a machine to convert thermal energy from the environment into useful energy [4, 5].

We shall point out here that one can also utilize the aforementioned mechano-caloric effect to convert thermal energy into useful energy, in a way similar to that proposed in Ref. [4], however, this energy generation is more complicate and less efficient than that in [4].

This energy generation involves one kind to low temperature heat apparatus which works like a heat engine. The heat apparatus absorbs heat from a high temperature heat source, converts part of the heat into work (or other useful energy) and releases the rest of the heat to a low temperature heat source. In the mechano-caloric effect plotted in Fig. 1, when the temperature difference between two vessels is significant (for example, with ΔT is the order of a few hundred mK), an efficient low temperature heat apparatus can operate between two vessels and convert part of the thermal energy of superfluid helium into another form of energy which is released into a room temperature environment. Once the temperature difference between two vessels is no longer above a workable value, then it can be implemented to transfer the superfluid helium from one vessel and to join the transfered liquid into the superfluid helium in the other vessel, then this mechano-caloric effect can start again to build a significant temperature difference between two vessels, and the whole process can be repeated forever. The intermittent superfluid transfer needs energy input, but one can show that this energy input (for one transfer) can be as small as the change of gravitational potential energy of liquid helium in the process (1)$\longrightarrow$(2)$\longrightarrow$(3) plotted in Fig. 1, and it can be much smaller than the energy released by the heat apparatus between two consecutive superfluid transfers, providing the heat apparatus have a good energy-converting efficiency. Hence, this energy input will not pose an issue in principle. The lose of thermal energy of superfluid ^{4}He system is compensated by the heat passed to it by a second type of heat apparatus, which works between a room temperature object and this superfluid ^{4}He system as its low temperature heat source. Obviously, this second type of heat apparatus is responsible for generating the bulk of the useful energy. Some difficulty such as unavoidable thermal radiation can be handled in the same way as that discussed in Ref. [4].

Since the mechano-caloric effect can be used to convert thermal energy into useful energy in principle, or equivalently, implying the existence to a perpetual motion machine of the second kind, it is natural to conclude that the second law of thermodynamics is not a universal law.

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