Justification for the Possibility of Hydrogen Use as a Refrigerant in Hypervelocity Vehicles

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The study considers the method of heat accumulation during the operation of hypervelocity vehicles (HV) in a rarefied medium and vacuum. We present the justification for creating an active thermal protection unit (heat regenerator) and the choice of a refrigerant in terms of its weight and specific cost. The paper suggests a methodology on how to calculate the cost of different types of refrigerants depending on the modes of the HV operation. We analyze the use of hydrogen as a refrigerant and also outline the way to improve the design of the hydrogen heat regenerator and the possibilities of its application with the HV.

Keywords: *evaluation measure, heat regenerator, hydrogen, hypervelocity vehicle (HV), refrigerant, transport, vacuum, weight.*

Introduction

With the technological advancement, all processes in today's world are becoming more rapid. The speed of movement of people and goods is no exception. Global transport companies regularly offer innovations with improved performance, which solve the problem of speed and profitability of transportation [1, 2], and therefore, improve the level and quality of life, contribute to economic development. Currently, the increase in the speed of vehicles is considered both in the context of urban transportation systems [3] and in intercity and interregional rail and motor traffic [1, 4, 5].

One of the solutions to increase the speed of ground transport is the creation of hypervelocity transport complexes that provide for the movement of vehicles in a rarefied medium in airtight tunnels. This approach enables to reduce the resistance of the environment to motion and to minimize the power used by engines, as well as the overall energy consumption.

Traditional vehicle cooling systems rely on the transfer of thermal energy from a heat source (engine, electrical equipment, human, etc.) to the radiator to dissipate it through blowing by the ram air flow. If there is no sufficient amount of ram air (for example, when the vehicle moves in highly rarefied gaseous medium) the process of heat transfer by convective method to the external environment gets complicated. When the vehicle moves in a complete vacuum (particularly in space), this process becomes impossible. The complex dependence of the amount of dissipated energy on the environmental parameters and the vehicle's speed does not allow a high degree of accuracy to assess the performance of the convective cooling system of vehicles running at different speeds on Earth and in space. The hypervelocity vehicle (HV) also operates in such difficult conditions at speeds above 1,000 km/h. Consequently, it is inefficient to use convective cooling systems; here we should consider other ways of heat abstraction (for example, by its radiation or autonomous conversion into another type of energy). As an option to cool the vehicle in a rarefied medium, we propose a device of on-board heat converters and the possibility to recharge them at the terminal stations.

Justification for the Use of Hydrogen as a Refrigerant

Any moving vehicle generates heat; its amount depends on the efficiency of the systems engaged, as well as on the drag forces that need to be overcome. Increasing the efficiency and reducing the resistance to motion is one of the ways to solve the problem of heat while the vehicle is running.

During the operation of a ground vehicle, a considerable share of the engine power is spent on overcoming the aerodynamic resistance of the air environment and the wheel rolling resistance. It is possible to improve the movement profitability of a vehicle by reducing these parameters. In some cases, resistance to movement is reduced by magnetic levitation [6, 7]. This method allows to elevate the vehicle above the roadway through the electromagnetic field. Another positive effect of this technology is a low noise level in motion. The downside is high capital and operating costs [8, 9], as well as insufficient efficiency of electromagnetic levitation systems (lower than that of a steel wheel).

Another way to cut the energy and cost of travel is to reduce the drag by depressurizing the medium. The essence of this concept is that the vehicle is placed in a pipe, from which air is pumped out to the desired value of rarefaction. The described approach is often combined with magnetic levitation [10]. In addition, there are other theories about the transport drive method in a rarefied medium: the air collected in front of the frontal part of the vehicle after being compressed in the compressor is fed under the lower part of the vehicle body to center it and avoid touching the tunnel walls [11].

Studying this aspect, we should pay attention to the experience of the HV development, see the invention in [12], where the above-mentioned problems are solved. The HV is meant to be a passenger or cargo wheeled vehicle moving on a track structure, which is located in the tunnel, made as a sealed pipe and filled with hydrogen under reduced pressure.

When designing the HV, there are a great number of issues that have not previously appeared in the context of transport complexes. In particular, when a vehicle moves in a rarefied medium, it is inevitable that there are difficulties with the abstraction of heat from the engine, power source, ventilation and air conditioning system of the cabin (heat emissions from passengers and on-board systems).

The simplest and most popular method of cooling technical devices is self-ventilation. This means that cooling occurs due to the ram air flow and its intensity is practically unregulated. It is possible to increase the intensity through forced air cooling – by installing another fan [13]. In rarefied medium conditions, such method is ineffective, because the density of the medium decreases in proportion to the pressure, and, accordingly, the amount of absorbed heat with the same parameters goes down. Although the tunnel is filled with hydrogen [12], which has a value of thermal conductivity coefficient much higher than air, it is necessary to cool the tunnel itself to prevent the medium from overheating.

To reduce the size of the cooling system for the same thermal capacity, it is possible to use liquid cooling, which is a conventional radiator system, the heat from which should also be abstracted to the environment [14], which is not applicable in these conditions. There are additional requirements for the heat abstraction system for a vehicle moving in a vacuum: the minimum possible weight and volume of the system, which affect the weight and volume of the vehicle itself.

Since in a rarefied medium there is no possibility to abstract the heat to the environment, we propose to arrange on board a cold accumulator with a capacity sufficient to absorb the heat, which is released during a trip between the terminal stations. The laws of thermodynamics say that a substance is able to absorb the maximum amount of heat during phase transition (evaporation and melting). It is worth considering this statement when developing evaporative or fusion cooling systems, which exhibit the highest effectiveness with the maximum compactness of the system [15].

Note also that in some systems the pre-treatment of the fuel mixture (to improve the efficiency of the engines) is associated with the accumulation of excess energy, i.e., useful energy is taken from the heat to be abstracted. Thus, there are trucks that use liquefied nitrogen or liquefied air as their source of energy. These substances pre-vaporize, absorb a certain amount of heat, and then are sent to the piston engine and drive the vehicle with better efficiency. This means that the same substance is used not only to drive the vehicle, but also to cool the engine, on-board systems and refrigerated compartment (for special-purpose vehicles) [16, 17].

Besides, this approach is described in the concept of cooling a capsule moving in a magnetic levitation tunnel (Hyperloop Alpha project [18–20]), where helium cooled to −269 °C is used (it is transported on board in a liquid state). Based on the Hyperloop concept, the air fed under the capsule after being compressed in the compressor is cooled with water during a phase transition. The resulting water vapor is stored on board the vehicle until the end of the trip, after which the vehicle is refueled. Solid phase transition batteries, namely ice batteries, which are widely used in the food industry, and most often in the dairy industry, are popular for solving certain problems [21]. In such batteries it is possible to use not only ice, but also other refrigerants: freons, water solutions of glycols and of salts.

Attention should be paid to the creation of the cooling system in aircrafts [22]. In particular, forced cooling is proposed, the so-called active thermal protection systems. In [22], hydrogen is firstly used as a refrigerant (it is directly heated in a cooling jacket or cools a liquid-metal coolant individually), and then sent in heated form to do useful work to an electric turbo-generator and rocket engine. However, the above study does not focus on the pre-heating state of hydrogen. From the viewpoint of the effectiveness of the refrigerant application by weight, it is more reasonable to use hydrogen for heating in the liquid state. Solution of safety problems is the second phase in the development of this direction, which can be the topic of the next study.

Based on the above, it is important to consider the cooling system of a vehicle not as a simple means to accumulate cold, but as a more complex process of heat exchange, involving not only the accumulation of heat, but also combining its conversion and further use for the HV.

The energy source of the HV movement through a tunnel can be an electrical energy storage (power batteries), a contact network or a hydrogen fuel cell (FC) that generates the energy to be consumed immediately on board the vehicle [12] (Figure 1).

When moving in a vacuum, it is not possible to abstract heat to the external medium; therefore, the vehicle must have

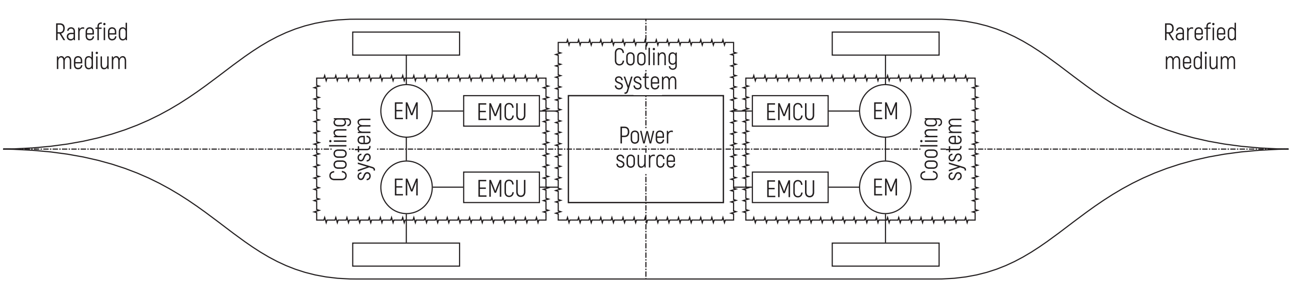

Figure 1 – Diagram of the HV power plant:
EM – electric motor; EMCU – electric motor control unit

an energy storage device capable of absorbing all the heat released during the trip. This paper considers the following substances as refrigerants: ice, liquefied hydrogen and liquefied oxygen. We also describe the "liquefied hydrogen – liquefied oxygen" system in the ratio of consumption, which ensures continuous operation of the hydrogen FC that produces water as the by-product. Ice is chosen as a refrigerant that has been widely and long used for similar applications. Once evaporated and heated to the operating temperature, the hydrogen can be discharged into the tunnel, which assumes a hydrogen environment with lowered pressure; the excess hydrogen will be continuously pumped out by pumps designed to maintain the desired pressure. In the "hydrogen – oxygen" system, two refrigerants after evaporation and heating to the operating temperature are used in the hydrogen FC, which utilizes water as the additional substance during its operation.

The amount of heat absorbed by hydrogen and oxygen was considered when they are heated to the resultant temperature of 37 °C, which allows engaging them further to power the FC. The resultant temperature of molten ice heating is 55 °C, because water is used only for heat absorption and there are thermal energy sources with a temperature of about 77 °C on board the vehicle. Initial values of parameters for each substance differ, which also determines the complexity and energy consumption in obtaining the required indicators of the refrigerant before loading that battery into the vehicle. For hydrogen the reference point is the state of saturated liquid with a temperature of about –253 °C; for oxygen – the state of saturated liquid at –183 °C; for ice two variants are possible: non-melting ice at 0 °C (0 °C ice) and supercooled ice at –100 °C (–100 °C ice).

The heat absorbed by the cold accumulator is taken up by the refrigerants in many processes, which should also be separated physically by installing several heat regenerators. Thus, the temperature of the working body of the cooling system in them will be different, which will allow obtaining cold of different temperature levels for any system.

When the 0 °C ice is involved, the heat is first consumed to convert the entire weight to a liquid state, and then to heat it up. An accumulator with supercooled ice will additionally include a heating stage of ice from –100 °C to the melting temperature. If liquefied hydrogen is used, the heat will be absorbed during its evaporation, and then during heating of gaseous hydrogen to the operating temperature. The case is similar with liquefied oxygen, which will require two heat regenerators. The most complicated and massive system is the "liquefied hydrogen – liquefied oxygen" system, which requires two separate sets of equipment for parallel operation of hydrogen and oxygen, since their further use in the FC is assumed (Figure 2).

This paper compares refrigerants through the theoretical analysis of the effectiveness of particular refrigerants by calculating the amount of heat absorbed and processing of the data obtained. The calculations were made taking into account the temperature dependence of the thermophysical properties of substances based on [23].

Figure 3 shows the dependence of the heat absorbed by each refrigerant on temperature. The amount of absorbed heat is given per 1 kg of substance; in case of the "liquefied hydrogen – liquefied oxygen" system – per 1 kg of water obtained from a reaction in the FC.

For the given resultant temperatures, 1 kg of hydrogen can absorb the greatest amount of heat – 4,150 kJ; pure oxygen (for comparison) – 415 kJ; the "hydrogen – oxygen" system – 830 kJ; the –100 °C ice and the 0 °C ice will absorb 709 kJ and 570 kJ, respectively (the difference in the amount of energy is due to heating ice from –100 °C to 0 °C) (Figure 3).

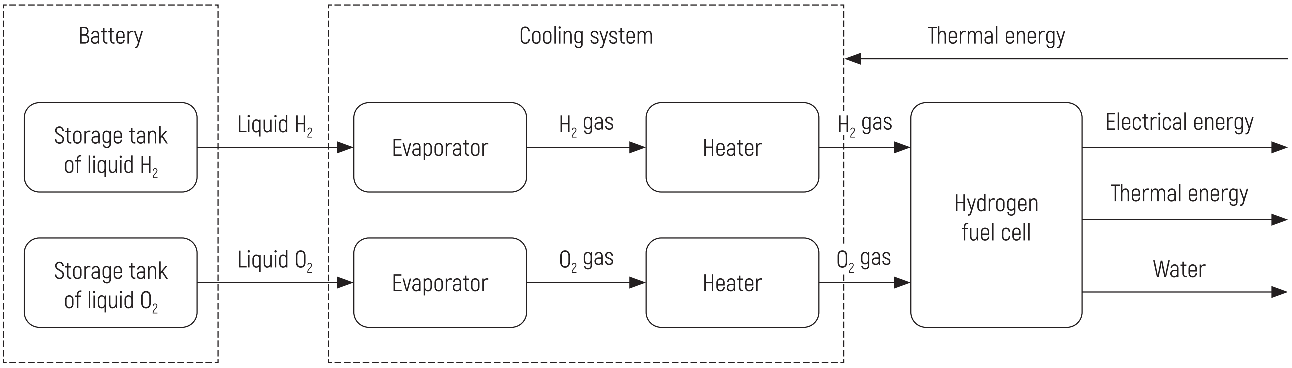

Figure 2 – Diagram of the use of hydrogen and oxygen as a refrigerant and energy sources on board the HV

That is, one of the most efficient refrigerants (with their equal weight) is liquefied hydrogen, which absorbs five times more heat than the second most efficient system based on hydrogen and oxygen. The least amount of heat among the proposed options is absorbed by oxygen upon its evaporation and heating up to 36.85 °C.

Heat emission generators in the HV are a power plant consisting of an energy source and an electric motor, as well as an air conditioning system, the capacity of which is determined by the heat emissions from passengers and on-board electronics. Both an electric battery and hydrogen FC can be used as the energy source (as per the patent [12]).

Consider, for example, the HV with travel time between the endpoints of 30 min. The vehicle is designed for six passengers, the mechanical power of the engine is 100 kW, and the mechanical efficiency of the engine is 90 %. Electrical energy is supplied to the engine from the FC, which has an electrical efficiency of 40 %. The power of heat emission by one passenger at rest is 0.1 kW. The heat emission capacity of the on-board electronics is 1 % of the FC electrical energy. The diagram of the HV heat flows and their estimated capacity are shown in Figure 4.

For the case in question, the heat flow capacity is 179.5 kW; the amount of energy to be accumulated during

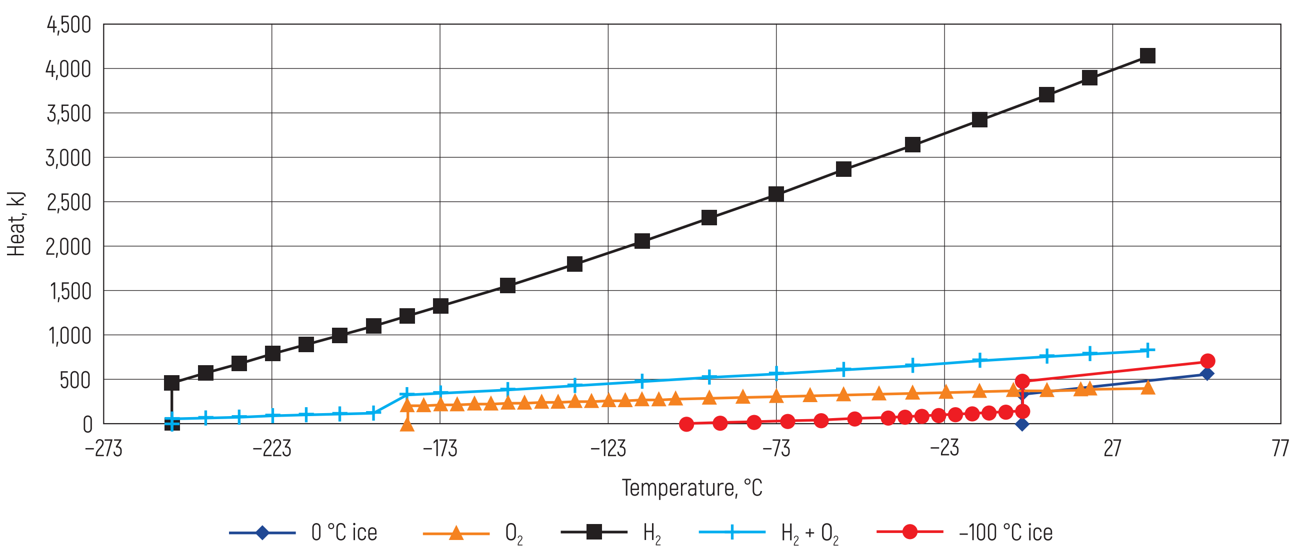

Figure 3 – Dependence of heat absorbed by the refrigerant on temperature

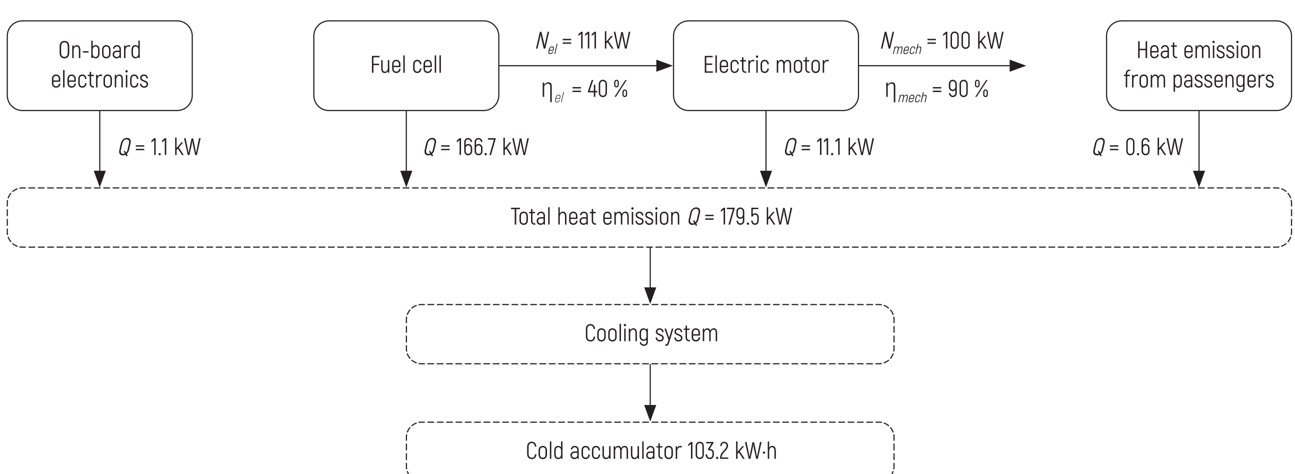

Figure 4 – Flows of excess thermal energy of the HV and their estimated capacity

the vehicle's movement: 179.5 × 1.15 × 0.5 = 103.2 kW·h, or 371.52 MJ (1.15 is a factor to account for capacity reserve).

Next, we will compare the given refrigerants by the weight of the substance, as well as by the cost of refueling per trip. The weight of the system is an important factor, since with a significant increase in the vehicle weight, the engine power rises, and, accordingly, heat emission does too.

The heat recovery system must provide complete absorption of the heat released by other systems. The heat balance equation can be represented as follows:

$$1{,}15Q_{abstr} = Q_{ref}, \tag{1}$$

where Q_{abstr} – heat to be abstracted from the power plant and the air conditioning system, kJ;

Q_{ref} – design heat for recovery by refrigerant, kJ.

The amount of refrigerant is calculated depending on the process in which the latter absorbs heat: heating or phase transition.

When heating, the refrigerant flow rate G (kg/s) depends on the temperature difference at the beginning and the end of the process Δt and on the heat capacity of the substance at the given temperatures c_p:

$$G = \frac{Q_{ref}}{c_p \Delta t}. \tag{2}$$

When a substance in the heat absorption process changes from one physical state to another, its amount will depend on the heat of phase transition r, which is an individual property of the substance and is determined by pressure:

$$G = \frac{Q_{ref}}{r}. \tag{3}$$

For the case with supercooled ice, when it is first heated with a temperature change to Δt^i, then the resulting water melts and is heated with a temperature difference Δt^w, the formula will look as follows:

$$G = \frac{Q_{ref}}{c_p^i \Delta t^i + r + c_p^w \Delta t^w}, \tag{4}$$

where c_p^i – weight isobaric heat capacity of ice, kJ/(kg·°C);

c_p^w – weight isobaric heat capacity of water, kJ/(kg·°C).

The above formulas show that in order to increase the effectiveness of the cooling system the refrigerant with the highest heat capacity must be selected.

Table outlines the specific production cost of 1 kg of refrigerant [23–25] in an evaluation measure (em), which at the first stage can be equated to one euro.

Table – Specific production cost of refrigerants

Refrigerant	Specific cost C, em/kg	Note
0 °C ice, C_1	0.13	
Liquefied oxygen, C_2	0.5	
Liquefied hydrogen, C_3	5.4	
Hydrogen + oxygen, C_4	1	$C_4 = 0.11C_3 + 0.89C_2$
–100 °C ice, C_5	0.19	

Refrigerant cost per trip $C_{p.t.}$ (em) to accumulate the released energy will be determined by the following dependence:

$$C_{p.t.} = GTC, \tag{5}$$

where T – trip time, s;

C – specific cost of the refrigerant with the required parameters, em/kg.

Figure 5 illustrates the results of calculations based on the dependence (5) of the amount of refrigerant to fill the battery for one 30-minute trip and the cost of this amount of the refrigerant with the parameters considered.

The smallest weight of refrigerant is required in the case of liquefied hydrogen, which is 90 kg for the given conditions (Figure 5). In the case of liquefied oxygen, the maximum required weight of refrigerant is 10 times more. In terms of the cost, the most favorable variant is the 0 °C ice: 87 em per trip. It is followed by the –100 °C ice with 99 em. The highest cost is in the case of liquefied hydrogen, which is 483 em.

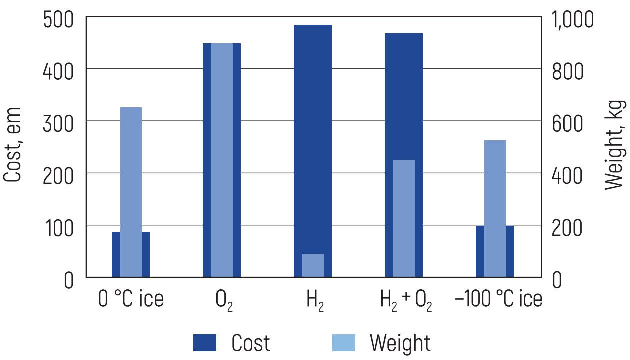

Figure 5 – Cost and weight of the refrigerants in the battery per one HV trip

For the parameters of the vehicle described above, the amount of electrical energy consumption per trip will be 55.6 kW·h, and the amount of heat to be accumulated (taking into account the capacity reserve factor) – 103.2 kW·h. Figure 6 shows the specific cost of refrigerants per 1 kW·h of electrical energy consumption per trip, when using the hydrogen FC as a power source.

Figure 6 demonstrates that the 0 °C ice is the most cost-effective refrigerant, while liquefied hydrogen is the least cost-effective option (with corresponding specific costs of 1.6 and 8.7 em/kW·h). However, if we consider the systems where the refrigerant weight is an important parameter (space rockets, HV, etc.), the use of hydrogen is already considered to be the most effective way of cooling. Furthermore, the cost of refrigerant depends on many factors and can change with time, what can not be said about its weight.

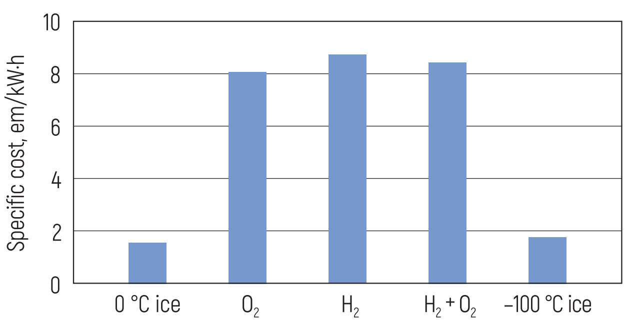

Figure 6 – Specific cost of the refrigerants per 1 kW·h of electrical energy consumption per one HV trip

To implement the model for the use of liquid hydrogen for heat recovery, we propose to choose the diagram shown in Figure 7. The hydrogen boiling process happens directly in the Dewar vessels, which are essential for the transportation of liquid hydrogen. This solution will allow to increase safety and optimize labor intensity of handling liquid hydrogen. An enclosed circuit with the refrigerant with a transition temperature to the solid phase below the temperature of liquid hydrogen (helium can be used as a refrigerant) ensures flow circulation and heat input for boiling exactly into the Dewar vessel. The level of liquid hydrogen declines as it boils and the working part of the liquid immersion circuit decreases. To maintain the required volume of recovered heat, we suggest changing the capacity of the pump that circulates the refrigerant through the enclosed circuit.

It is possible to connect to this heat exchange circuit secondary circuits with heated air streams or circuits of other

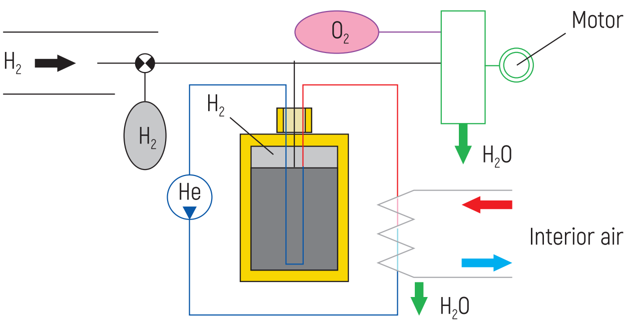

Figure 7 – Working diagram of the hydrogen heat converter

refrigerants from the vehicle interior, engines or other elements that require cooling. The use of secondary circuits will allow the effective treatment of the refrigerants circulating in them (for example, to separate the water contained in the cooled air, which could clog the secondary circuit if it freezes).

The gaseous hydrogen obtained by boiling in the Dewar vessel flows into the hydrogen FC power system, which can be fed with gaseous hydrogen from a separate tank or trunk designed for the vehicle. This solution contributes to power generation regardless of the presence of hydrogen gas in the medium where the HV is moving or the amount of emitted gas in the Dewar vessel.

Conclusions and Future Work

This paper is the first part of an extensive study of heat recovery effectiveness based on the thermophysical properties of substances used as refrigerants. In terms of the minimum refrigerant weight, the optimal substance is liquefied hydrogen.

To make a complete assessment of the use of liquid hydrogen as a refrigerant, you should apply a comprehensive approach and consider other aspects: the volume occupied by the heat regenerator; the complexity of the equipment; the cost of the system when working with a particular coolant to ensure reliability and safety; the labor intensity of equipment replacement; requirements for safe operation and qualification of the service personnel. Besides, there is another important point – it is possible to implement the considered method of cold recovery with the existing vehicles. The method proposed in this study allows to do so.

When using liquefied hydrogen, the specific volume of waste (gaseous) and loaded (liquid) hydrogen also changes considerably. A distinctive positive effect when using hydrogen is a reduction in the weight of not only the refrigerant, but also the entire vehicle. When hydrogen gas is discharged into the tunnel, it is unavoidable that negative consequences arise – an increase in the power of the pumps that maintain the vacuum in the tunnel. For this reason, the discharge of excess hydrogen is undesirable.

This study focuses on the analysis of steady rectilinear movement, i.e., the movement of the vehicle with unchanged power. During acceleration and deceleration, the ratio of electrical energy consumed and thermal energy released will change as compared to a steady movement. Therefore, in the future, it is also necessary to calculate the thermal balance when the vehicle moves in the acceleration and braking sections, which can be another objective for the next research in this direction.

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