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Smart superconducting grid

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Abstract

Smart superconducting grid is a global network for CO_2 emissions-free renewable energy economy. The grid combines delivery of liquid hydrogen and electrical energy via superconducting pipelines. The paper reviews the development of the grid concept and the efforts in material science and engineering advancing its practical implementation. Original results are presented outlining an activity that targets the challenge of joining sections of pipelines, as well as manufacture of superconducting pipes. The focus is put on testing the quality of superconducting MgB_2 joints and coatings using the magnetic flux visualization technique of magneto-optical imaging.

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Keywords: superconductivity; liquid hydrogen; renewable energy resources; pipeline infrastructure; hydro-extrusion; superconducting paint

1. Introduction

In the transition to renewable energy resources, one of the important tasks is to substitute fossil fuels with a 'clean' fuel that does not emit CO_2. Currently vehicles, power stations, factories and many households consume large amounts of fossil fuels and strongly contaminate the environment with this greenhouse gas. The emissions lead to the rise of temperature and destabilization of the climate. A reasonable alternative to fossil fuels is hydrogen, which when burning does not emit CO_2. Since it is a light gas, the best way to use hydrogen is in the dense liquid form. As liquid, hydrogen is also a very good coolant. Moreover, its boiling temperature (20 K) is low enough to put

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many superconducting materials in the zero-resistance state. This creates a unique opportunity to employ superconductivity on a massive scale. Superconducting materials offer compactness, high efficiency, savings in energy and a range of applications not possible with any other materials. The benefits of superconductivity are expected to compensate for the energy spent on the liquefaction of hydrogen. All this would make hydrogen economy very attractive for investments and adaptation.

The liquid hydrogen economy can start with the development of infrastructure in the form of a superconducting grid delivering both liquid fuel (hydrogen) and electricity. The present paper describes the development of the supergrid concept and the recent advances in materials science and engineering that approach its practical implementation. First, a joining technique aiming to resolve the problem of connecting sections of a superconducting pipeline is described. Then, we show that the quality of the joints can be analyzed using the visualization technique of magneto-optical imaging (MOI) [1]. The processes involved in superconducting pipe manufacturing are also addressed, and the MOI is used to attest the quality of coatings obtained by the superconducting paint technique.

2. Supergrid

The concept of superconducting grid, or supergrid, in its modern form was formulated by Paul Grant in 2001 [2] shortly after the discovery of superconductivity in MgB_2 [3]. Indeed, MgB_2 is an important material that can be used in construction of supergrid, which would form the basis of liquid hydrogen economy [4]. As early as in 1967, Garwin and Matisoo suggested to use Nb_3Sn superconducting lines cooled with liquid helium to 4.2 K for the transmission of large amounts of electrical power over long distances [5]. The critical temperature (T_c) of Nb_3Sn is 18.3 K, which at that time was one of the highest T_c of the known superconductors. Building such a transmission line would require large capital investments as well as big amounts of liquid helium. In this design the liquid helium served as a coolant only. It would be far more efficient to use as coolant a fluid that is also a fuel, since then the delivery of electricity and fuel could be combined in the most efficient way.

Such a combined delivery was suggested in [6] in 1972. The choice of coolant was liquid hydrogen or liquid natural gas (boiling temperature 111 K). Since in 1972 there were no superconductors working at these temperatures, normal Cu lines were considered for the electricity transfer utilizing the low resistance of Cu at cryogenic temperatures.

In 1975, Haney and Hammond suggested [7] to reduce, by decreasing the operating pressure, the boiling temperature of liquid hydrogen to a temperature close to its limiting point of 14 K, where hydrogen becomes solid. Then, conventional superconductors could in principle be used for transfer of energy without dissipation. However, 14 K is too close to T_c for conventional superconductors and they are not very efficient at this temperature.

The discovery of high temperature superconductors in 1986 [8] changed the situation dramatically allowing to plan transfer of electricity by superconductors cooled by liquid nitrogen (77 K) [9]. Still, liquid nitrogen is not a fuel. Moreover, it is difficult to manufacture long-length lines of high temperature superconductors. Finally, after the discovery of superconductivity in MgB_2 with T_c of 39 K, the concept of the simultaneous delivery of liquid hydrogen and electricity via MgB_2 was adapted [2].

In all mentioned variants the transfer of electricity was considered through electrical cables placed in the pipes and cooled by the flowing cryogen. The first experimental proof of concept for an MgB_2 cable cooled by liquid hydrogen was reported in 2013 [10]. In [4], a simpler concept was suggested excluding cables, making the pipe itself superconducting and delivering electrical current along the pipe while pumping liquid hydrogen inside. Superconducting pipes offer higher superconductor cross-section than cables thus allowing higher currents to flow. As in [2], the superconducting pipes deliver both electricity and liquid hydrogen, and could be considered as main element of the infrastructure for the fossil fuels-free energy economy.

3 Infrastructure for energy economy

A schematic of the infrastructure for fossil fuels-free energy economy is shown in Fig. 1. The main feature of the infrastructure is that fossil fuels are not among the sources of energy. It is therefore CO_2 emissions free. The sources of energy are mainly renewable: solar, wind, marine, hydro-electrical, biological or long lasting: geothermal, nuclear. As a possible source, thermonuclear energy is also included in the infrastructure. All sources supply both electricity and liquid hydrogen, which are transported to cities via superconducting pipelines.

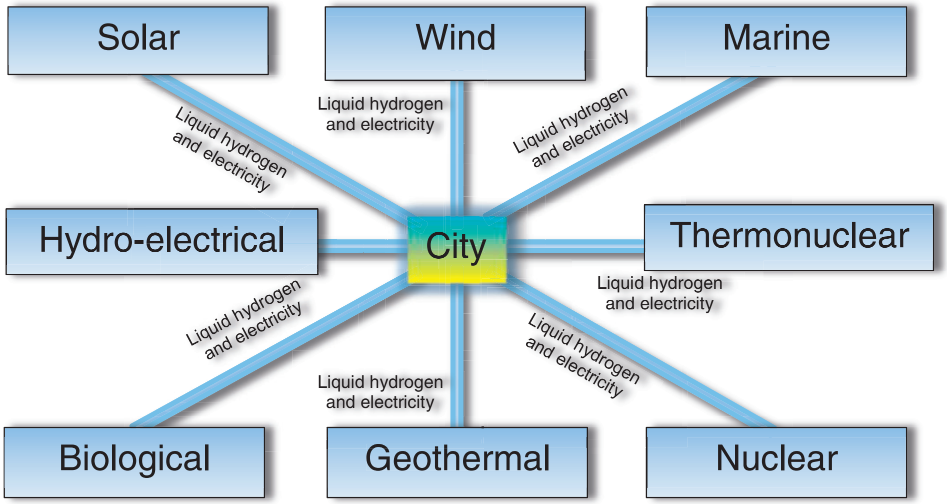

Fig. 1. Infrastructure for liquid hydrogen economy. No fossil fuels are among the sources of energy. All sources supply both electricity and liquid hydrogen, which are transported to cities via superconducting pipelines.

The production of superconducting pipes is one of the main challenges of the infrastructure. As of today, the most likely pipe material is MgB_2. This is a material with high critical temperature, nearly twice that of the boiling temperature of liquid hydrogen and also a high critical current, up to 10^6 A/cm^2 at 20 K. Moreover, the mass density of 2.62 g/cm^3 is low, being 3 times lighter than stainless steel.

Two types of superconducting pipes would be necessary. One type with relatively small diameter (~20 cm) and thick walls (~1 cm) is needed mainly for the compact transport of electricity. Another type of a large diameter of about 1 m with thin superconducting cover would be used mainly for the transport of liquid hydrogen.

The first type of pipes could be produced by hydroextrusion. Schematically the cross-section of an apparatus for production of such a pipe is shown in Fig. 2. The apparatus contains a chamber heated to about 800 °C to which MgB_2 powder is supplied. The heated MgB_2 is pressed by a tungsten former of a special configuration allowing to form the pipe by solidification outside the chamber. After producing a section of pipe, the former is slowly retracted sliding inside the solidified pipe. Simultaneously MgB_2 powder is added, and this is repeated in a continuous process. In principle the pipe could be of any length. Tungsten is expected to perform well in this apparatus. It has already been tested with MgB_2 in the technique of resistive sintering [4].

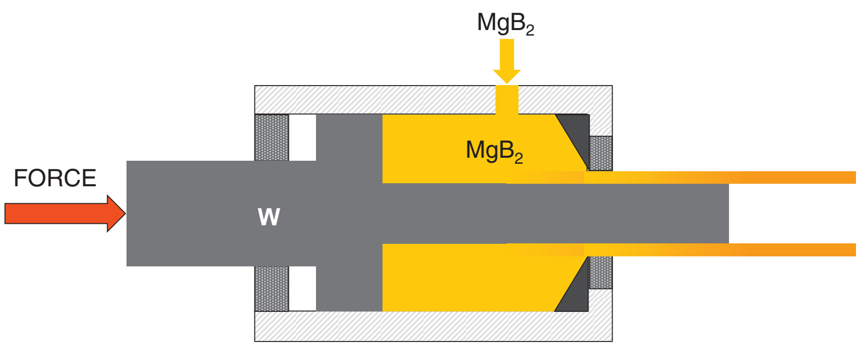

Fig. 2. The hydroextrusion apparatus for production of MgB_2 pipe. The powder is heated to about 800 °C and pressed by a tungsten former of a special configuration allowing formation of the pipe by solidification outside the chamber.

4. Superconducting joints

While the hydroextrusion process is continuous, it may be convenient to produce sections of the pipe of finite length and join them when constructing the pipeline. For that it is necessary to make joints between pieces of superconductor that would support nearly the same superconducting current as in the bulk. It is a challenging task for any superconductor excluding perhaps some low-T_c elemental metals and alloys. Recently, it was showed that joining two pieces of bulk MgB_2 indeed is possible [11]. The high quality of the joints was confirmed by magneto-optical imaging (MOI), a versatile technique able to visualize the magnetic flux penetration, and thereby also the current-carrying ability of superconductors, in particular those suitable for hydrogen applications [12].

After completing this step the further progress in this direction was to produce serial joints. This was first done by connecting in the processing apparatus described in [4] two pieces of superconductor and then adding another piece and re-processing the sample. It is found that multiple processing does not degrade the superconducting properties of MgB_2, and the quality of all the serial joints is found to be high.

Shown in Fig. 3 is an example of magnetic flux penetration into a sample with double superconducting joint imaged by MOI at three temperatures of 20, 35 and 36 K. The position of the joints is marked by white arrows. At 20 K, which is the operation temperature for the superconductor immersed in liquid hydrogen, the joints are not visible in any way (Fig. 3a). It indicates that the critical current through the joints is essentially as high as in the bulk MgB_2. When the temperature becomes closer to T_c, magnetic flux starts entering the sample (dark areas penetrating the bright area of MgB_2) preferentially along the joints, see Fig. 3b showing the jointed region at 35 K. This tendency continues at higher temperatures, as evident from the image recorded at 36 K (Fig. 3c). The sample in Fig. 3 was prepared from ex-situ commercial MgB_2 powder. The joints in the sample are even harder to see than in the nanoparticle added sample described in [11]. However, T_c and critical current density in such a plain MgB_2 sample is lower than in samples with nanoparticles. Overall, several experiments show that serial joints can be of high quality in various MgB_2 samples, and that the multiple processing of MgB_2 is not reducing their quality.

The jointing technique described in [11] could be scaled up to connect pipes in commercial pipelines. Small pieces of MgB_2 pipes (tubes) are already available and used for screening of magnetic field [12]. In [12], they were prepared by the magnesium infiltration technique [13], which could be another process for production of pipes. In a pipeline, pipes need to be properly thermo-insulated, ideally with vacuum. A section vacuum approach to solve this problem was developed in [10].

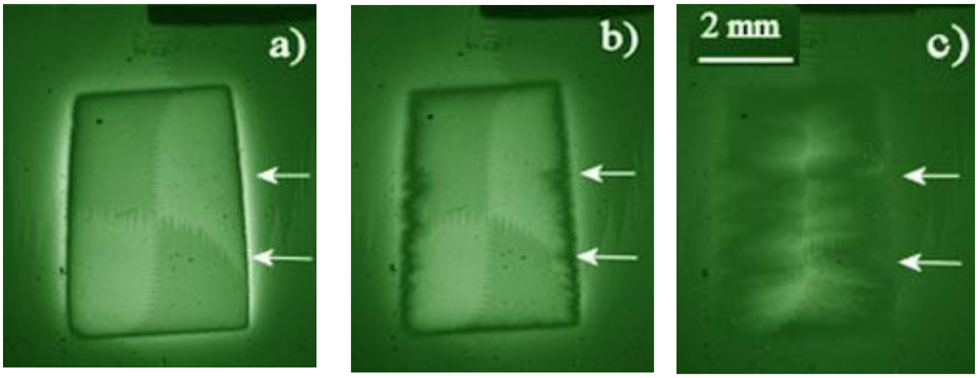

Fig. 3. MOI images of the trapped magnetic flux in the sample with two superconducting joints at temperatures 20 K (a), 35 K (b) and 36 K (c). The superconductor was field-cooled to 20 K in magnetic field of 17 mT. The position of the joints is shown by arrows.

5. Superconducting paint coating

For the pipes of large diameter and thin layer of superconducting coating the paint technology is a more suitable option. The superconducting paint could be either MgB_2 powder-based [4] or amorphous boron-based [15]. Both require thermal treatment in vacuum or in Mg vapor. Preliminary measurements of MgB_2 powder-based paint covers were reported in [4]. In this technique, MgB_2 is mixed with carbohydrates. During the heat treatment, carbohydrates are decomposed with carbon going into the crystal lattice of MgB_2 improving its superconducting properties. The hydrogen is released and can be collected for general use. No CO_2 is created in the process.

Fig. 4 shows magneto-optical images of MgB_2 powder-based superconducting coating at temperatures 3.7 K (a) and 20 K (b). At both temperatures a complete screening of the magnetic flux in the coating is observed, indicating its good quality.

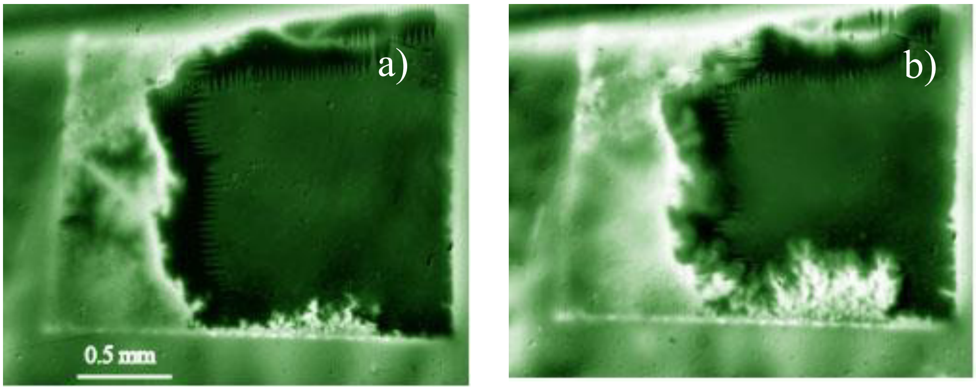

Fig. 4. MOI images of the screened magnetic flux in superconducting paint coating at temperatures 3.7 K (a) and 20 K (b). The images were recorded after zero field cooling and application of the magnetic field of 8.5 mT.

The images were recorded after zero field cooling and application of the magnetic field of 8.5 mT. At this field, magnetic flux penetrates into the sample in a non-uniform way following the weakest paths between the MgB_2 grains. The good screening seen in the right part of the sample is in stark contrast with what is seen in the left, heavily deformed part of the sample where magnetic field easily penetrates the coating.

6. Smart superconducting grid

The superconducting pipelines could form the basis of a smart superconducting grid. This grid would cover electricity and fuel supply, distribution and use in one interconnected and automatically controlled system. In the grid, the control of both fuel and electricity flow would be possible over very large distances since there is no distance limitation for the losses-free superconducting current flow. The intermittent energy sources such as wind power generators would supply mainly liquid hydrogen into the grid, while continuous generation, for example in nuclear power stations would provide mainly electricity. When the demand for electricity is low, part of it would be automatically re-directed to produce more liquid hydrogen. If the demand for electricity increases, the fuel cells would be used to produce electricity from the stored hydrogen.

A smart grid of this type would be controlled by advanced superconducting electronics as well as conventional electronics operating at low temperatures, where it shows higher stability and efficiency than at room temperature. The availability of low temperatures and superconductivity in pipes of large cross-section, big surface area and possibility to be connected to the superconductor whenever it is necessary, would modernize collection and transfer of information constantly monitoring energy flow rate, condition of the grid, energy supply, demand and preferences of the consumers.

The system would be self-protected by the superconducting fault current limiters. First superconducting fault current limiters were found to be very useful [16] even in the conventional electrical grid. It would be natural to introduce them all over supergrid. In the future, supergrid would be controlled by the powerful superconducting computers that are under development now. It is not excluded that these would also be low-temperature quantum computers.

Using superconductivity, it would be easier than in the current designs to address such functions of the smart grid as demand-supply adjustment, load balancing, theft/loss prevention, fault detection, self-healing, security monitoring and correction in prices for fuel and electricity. It is hard to compete with superconductivity in efficiency and compactness, and superconductivity is the integral part of the supergrid. This variant of grid is also designed specifically for renewable and CO_2 emissions-free sources of energy. It will be equipped with natural for the system energy storage in liquid hydrogen tanks and superconducting magnetic energy storage systems [17]. There is a hope that such self-controlled network delivering both liquid hydrogen end electricity may eventually become the reality of the fossil fuels-free energy economy.

7. Conclusions

A concept of supergrid is discussed. The approaches to build it as infrastructure for fossil fuels-free energy economy were discussed. Following the recent advances in the materials science and characterization, it is shown that smart superconducting grid is a viable option for the future energy economy.

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