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Review

Review on magnetic refrigeration devices based on HTSC materials

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The development of a high-efficiency magnetic refrigerating machine (magnetic refrigerator) with a superconducting magnetic field source operating in the room temperature range is currently an actual scientific and engineering problem. The analysis of scientific and technical literature, regulatory documentation, other materials as well as existing patent landscape for the specified topic is carried out in the paper. Main areas of further research are considered, and comparative assessment of their efficiency is carried out. Different concepts of the magnetic refrigerating machine with a superconducting magnetic system are discussed including general schemes of implementation of both the machine and its assemblies.

Étude des dispositifs de froid magnétique basée sur des matériaux supraconducteurs à haute température

Mots-clés: Machine frigorifique magnétique; Effet magnétocalorique; Supraconductivité à haute température

1. Introduction

1.1. Artificial cooling technologies

Currently artificial cooling, including air conditioning, implemented using refrigerating (heat) machines is widely applied in industry, daily life, and commerce. In addition, heat machines are widely used as heat pumps providing cold-to-warmer-level heat transfer. Besides daily use, the heat pumps can be also used commercially for reprocessing of low-potential waste heat in cooling towers and others. From the point of view of cost efficiency, usage of heat pumps is more efficient than direct heating by fuel burning or by electricity (the advantages of heat pumps are considered in details, in particular, in Rognon (2005)).

Vapor-compression-type heat machines are at present time most often applied for artificial refrigeration using evaporation-condensation and compression-expansion thermodynamic cycles, and as a working substance (in magnetic refrigeration technology the term 'working body' is used (Tishin and Spichkin, 2003), therefore, this term is further used in the description of other cooling methods) – a vapor transforming at certain cycle stages into liquid. A motor-driven mechanical compressor provides compression and expansion in these devices. Today vapor-compression technology that has already been improved for over one hundred years has practically been achieving its upper limit of development, and further essential improvement of its power efficiency could hardly be expected (Domanski, 1999; Maidment, 2010). Therefore, the task of designing reliable and eco-friendly heat machines operating within the temperature range from −30 to +50°C remains actual.

Currently, absorption refrigeration (Srikhirin et al., 2001), thermoelectric cooling (Riffat and Ma, 2003), and air cycle refrigeration (Gigiel, 1996) are considered to be alternative to the vapor-compression refrigerating technology. The absorption refrigeration is in many respects similar to the vapor-compression refrigerating technology, but compression–expansion cycle here

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is provided not by a compressor but by gas (working body) absorption/liberation from the absorbing material. Absorption refrigeration is used in chemical industry and in household absorption refrigerators. At the same time this cooling technology features much higher energy consumption than the vapor-compression technology. Thermoelectric cooling is based on semiconducting material cooling when electric current passes through it (Peltier effect) (Zhao and Tan, 2014). This technology does not require any coolants and compressors, but it is also characterized by very high energy consumption. Today thermoelectric refrigerators are mainly used as portable refrigerators for automobiles (Zhao and Tan, 2014). Refrigerating technology based on air (gas) cycle uses air compression-expansion cycles without evaporation–condensation. Historically, the air-cycle-based refrigeration appeared earlier than the vapor-compression technology, and was then forced out by the latter because of the low power efficiency at 0°C and higher temperatures. Air cycle-based refrigeration is used mainly to obtain cryogenic gases from the air and in the refrigeration plants of sea transport, where there are increased safety requirements for refrigerating equipment. Therefore, all the three considered kinds of refrigeration yield in power efficiency to the vapor-compression technology that is itself insufficiently efficient as to power consumption.

1.2. Magnetic refrigeration: background

Power efficiency problems of the currently used vapor-compression refrigeration technology can be solved by a magnetic heat (refrigeration) machine that can be used in the same areas where the vapor-compression heat machines are applied. Magnetic refrigerating machine is a cooling device which implements magnetic cooling technology based on magnetocaloric effect (MCE). MCE manifests itself in an adiabatic temperature change or an isothermal change in the magnetic part of the entropy of a magnetic substance with a change in the external magnetic field. MCE reaches its maximum value at temperatures close to the temperature of the magnetic phase transition of the magnetic material. As a working body in the magnetic refrigerating machine a magnetic material in solid phase is used that changes its temperature (heating–cooling) and magnetic part of entropy related to the magnetic system of the material while magnetizing–demagnetizing (because of MCE). This enables to replace the vapor-compression cycles of evaporation-condensation and compression–expansion with the solid body magnetization–demagnetization cycles. Theoretical estimates and the results of preliminary investigations demonstrate that the magnetic heat cycles are much more efficient than the vapor-compression cycles. The magnetic heat machine has the following advantages:

- high power efficiency (according to theoretical estimates, the magnetic refrigerator efficiency is about 85% of Carnot cycle in the temperature range from 150 to 300 K),
- less overall dimensions and weight as compared to vapor-compression devices due to considerably greater density of solid body versus gas,
- low wearability due to low operating frequency of magnetic heat machine,
- safety and ecological compatibility (working body is a non-toxic material, no chemical coolants are used).

The disadvantages of magnetic cooling devices include:

- higher cost of magnetic refrigerators (expensive sources of magnetic field and, possibly, magnetocaloric material of the working body);
- the presence of a magnetic field source may impose restrictions on possible applications of magnetic refrigerators.

Mentioned advantages will allow solving the problems of vapor-compression machines (refrigerators) and entirely replacing with time the vapor-compression refrigerating technology with the magnetic one. Being appropriately adapted, the magnetic refrigerating machines can be used in the same areas, where the vapor-compression machines are applied. Currently, R&D on magnetic heat (refrigerating) machine designing take place at research centres in most of the developed countries such as: USA (University of Ames, Iowa (Lee et al., 2002; Zarkevich et al., 2018; Zimm et al., 1998); Astronautics Corporation of America, Wisconsin (Jacobs et al., 2014; Zimm et al., 2018, 1998)), European Union (University of Applied Sciences of Western Switzerland (Chiba et al., 2014; Kitanovski and Egolf, 2010); G2Elab, Univ. Grenoble Alpes, France (Dupuis et al., 2009); Max Planck Institute, Germany (Ghorbani Zavareh et al., 2015); Cooltech Applications, France (Muller and Heitzler, 2014; Vasile and Muller, 2006; Vasile and Muller, 2005); University of Ljubljana, Slovenia (Kitanovski et al., 2015; Tušek et al., 2014, 2013); Technical University of Denmark – DTU, Denmark (Engelbrecht et al., 2012, 2011; Lozano et al., 2014); Mater. Science Institute Barcelona, Spain (Bohigas et al., 2000); University of Salerno, Italy (Aprea et al., 2016; Aprea et al., 2014)), Canada (University of Victoria) (Christiaanse et al., 2018), Japan (Chubu Electric Power (Toshiba)) (Hirano et al., 2002; Okamura et al., 2006), South Korea (Kim et al., 2013), China (Cheng et al., 2013; Zhang et al., 2013).

2. Magnetic field sources for a magnetic refrigerator: permanent magnets, LTSC, HTSC

The designs of magnetic heat machines that have been suggested and patented by now are based on the schemes with a magnetic field source assembled using permanent magnets or implemented using a superconducting solenoid made of traditional superconductors operating in the helium temperature range (low-temperature superconductors – LTSC) (Yu et al., 2010). It should be noted that the systems based on permanent magnets provide high-intensity fields (of about 1.5 T level) only in a narrow operating gap of about 1 to 2 cm width (Bjørk et al., 2010). This makes it impossible to place sufficient quantity of working body to the working space of the magnetic field source, which reduces refrigerating capacity of the whole device.

For generating magnetic field of high strength (over 10 T), superconducting magnetic systems have been used for over half a century manufactured based on superconducting Nb–Ti and Nb–Sn wires which transition to superconducting state requires cooling to the temperatures corresponding to liquid helium, i.e. these are LTSC. However, from the point of view of overall expenditures, usage of LTSC field sources to create a magnetic refrigerating machine does not seem to be promising. Liquid helium is quite an expensive consumable and it requires to be gathered to gaseous state after its transition. In addition to this, refrigerating systems based on two-stage cryogenic refrigerators (cryocoolers) consume essential power, which brings to nothing the advantages of magnetic refrigeration.

Today superconducting wires are actively developed in the world that are based on so-called “high-temperature” superconductors (HTSC) characterized by relatively high temperatures of transition to superconducting state (critical temperatures) – from 90 K to 110 K. HTSC materials based on perovskite ceramics make it possible to provide critical current density of up to 10 MA/cm^2 at 77 K temperature. Most promising are second-generation HTSC wires in the form of thin (40–100 µm thick and 4 to 12 mm wide) metal carrier ribbon with highly-textured buffer and superconducting oxide layers of up to 5 µm total thickness deposited on it. These ribbons are covered with copper layer to provide capability of soldered electrical connections. Usage of HTSC ribbons enables to

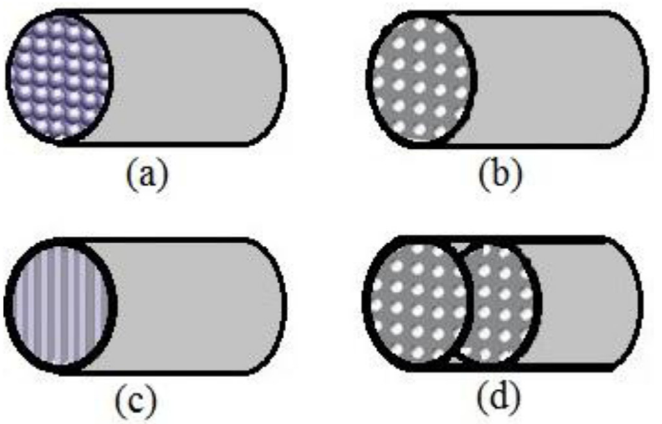

Fig. 1. Kinds of working body geometry (regenerator types): (a) regenerator with close packing of particles; (b) regenerator with longitudinal channels in a massive block (matrix); (c) regenerator composed of a set of flat plates (plate regenerator); (d) regenerator consisting of a set of perforated plates.

create solenoids with field intensity of 1.5 to 2 T in considerably greater working gap (of about 1 l volume) using liquid nitrogen cryogenic system, or using a single-stage cryorefrigerator.

Only one attempt has been made till now to use HTSC field source in magnetic refrigerating machines (Blumenfeld et al., 2002a). Currently, there are no commercial prototypes of magnetic refrigerating machines with HTSC magnetic field sources in the world market.

3. Active magnetic regenerator

Different thermodynamic cycles that require appropriate design solutions are used in magnetic heat machines.

The analysis of available literature devoted to magnetic heat machines (Allab et al., 2005; Chiba, 2017; Kitanovski et al., 2015; Kulkarni, 2015; Luiz Dutra et al., 2017; Yu et al., 2010; Zimm et al., 2018, 1998) shows that all currently known devices designed for cooling from the room temperature range operate following active magnetic regenerator (AMR) cycle. In this cycle, the magnetic material itself is used as a regenerator, and heat exchange during regeneration process takes place between the magnetic material and heat carrier, which prevents technical difficulties and losses due to the use of an individual regenerator as it takes place in the devices with Erickson and Brighton regenerative cycles.

Active magnetic regenerator is a container filled with a magnetic material in the form that allows passing of heat carrier through the regenerator. Magnetic material which geometry corresponds to the regenerator kind is commonly called a working body. Fig. 1 depicts possible kinds of working body and the types of magnetic regenerators corresponding to them.

Fig. 1a shows the regenerator with close packing of particles. The container of such a regenerator is densely filled with magnetic material particles. Here the particles of both spherical and arbitrary shape can be used. Heat carrier flow in the regenerator with close packing of particles passes through hollow space of the close packing. Fig. 1b shows a regenerator with longitudinal channels in the massive block of material. Here liquid flow passes through the channels along the long regenerator face. In the plate regenerator (Fig. 1c) the working body consists of flat plates with long edges parallel to the regenerator longitudinal dimension stacked in such a way that to keep gaps between the plates for heat carrier to pass through. Regenerator consisting of a set of perforated plates (Fig. 1d) has the plates with the holes located across the heat carrier movement. Regenerator container shall not necessarily be of a cylindrical shape as it is shown in Fig. 1 Regular-shape containers of uniform cross-section are selected as a rule. Cylindrical and rectangular regenerator containers are used in AMR heat machines (Yu et al., 2010). Some results of theoretical and experimental investigations of the various AMR fillings are presented in (Chiba, 2017; Keawkamrop et al., 2018; Nakashima et al., 2018a, 2018b; Shi et al., 2018; You et al., 2018).

Besides regenerators for AMR machines shown in Fig. 1, regenerators with working material in the form of a grid (grid regenerator) and thin ribbon (foil) winded as a coil (ribbon regenerator) are applied in cryogenic refrigerating devices – Fig. 2 (Ackermann, 1997).

As it can be seen in Fig. 2, the grid regenerator is essentially similar to the perforated plate regenerator shown in Fig. 1d.

Regenerator geometric configuration can be characterized using a number of parameters, including the following (Ackermann, 1997):

- matrix surface area A_s;
  - regenerator clear opening area A_{ff};
  - regenerator working material (matrix) porosity (porosity factor) α;
  - regenerator matrix surface density β;
  - regenerator matrix hydraulic radius r_h;
  - regenerator matrix hydraulic diameter d_h.

Nonregenerative Carnot cycles are used only in temperature range below 20 K, but even for this temperature range AMR cycles are used (Bézaguet et al., 1994; Hakuraku and Ogata, 1985; Jeong, 2014).

Creation of a specific magnetic refrigerator prototype requires implementation of its components and assemblies (magnetizing–demagnetizing system, magnetic regenerator with working body made of magnetic material, heat carrier transfer system).

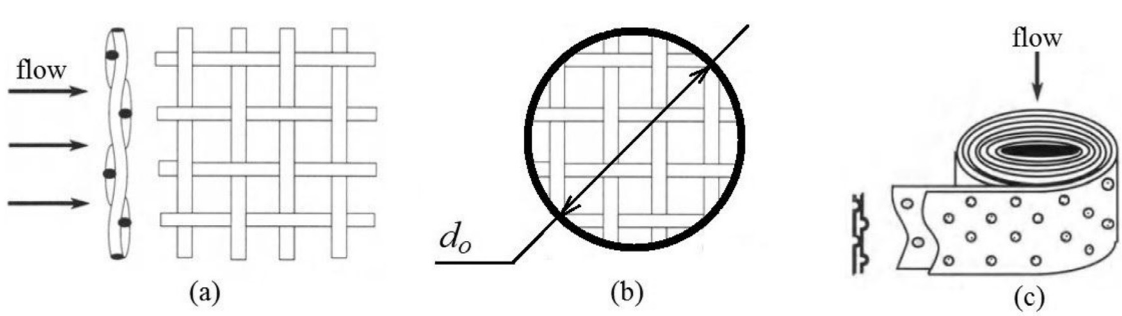

Fig. 2. Regenerators of cryogenic refrigerating devices: (a) with working material in the form of a grid (grid regenerator); (b) grid element of grid regenerator (d_o – inner diameter of regenerator container); (c) with working material in the form of coiled ribbon (ribbon regenerator) (Ackermann, 1997).

Table 1
Parameters of AMR heat machine with stationary switched superconducting field sources from Blumenfeld et al. (2002b), Green et al. (1990).

No.	Regenerator material	Field source type, generated magnetic field strength	Heat carrier transfer system	Heat carrier	Operating frequency of the device, Hz	Field rate of change, T/s	Reference
1	composed, Gd, Tb foil	LTSC, 7 T	displacer	nitrogen gas	0.014	0.23	Green et al. (1990)
2	Gd, 0.2 mm spherical particles	HTSC (Bi-2223), 1.7 T	displacer	water	0.033	0.2	Blumenfeld et al. (2002b)

Table 2
Data of AMR magnetic heat machine prototypes designed based on the scheme of regenerator linear back-and-forth motion and stationary magnetic field source (Arnold et al., 2011; Hirano et al., 2002; Richard et al., 2004; Rowe and Tura, 2006; Rowe and Barclay, 2002; Tura, 2005; Zimm et al., 1998).

No.	Regenerator material	Field source material, generated magnetic field strength	Heat carrier transfer system	Heat carrier	Operating frequency of the device, Hz	Field rate of change, T/s	Reference
1	Gd, 0.15 – 0.3 mm spherical particles	LTSC (Nb-Ti), 5 T	pump	water	0.16	5	Zimm et al. (1998)
2	Gd, 0.3 mm spherical particles	LTSC, 4 T	pump	water	0.17	2,7	Hirano et al. (2002)
3.1	Gd, spherical particles	LTSC (Nb-Ti), 2 T	displacer	helium gas	0.2 – 1.2	–	Rowe and Barclay (2002)
3.2	composed, Gd, $Gd_{0.74}Tb_{0.26}$	LTSC (Nb-Ti), 2 T	displacer	helium gas	0.2 – 1	–	Richard et al. (2004)
3.3	composed, Gd, $Gd_{0.74}Tb_{0.26}$, $Gd_{0.85}Er_{0.15}$	LTSC, 2 T	displacer	helium gas	0.65 – 1	–	Rowe and Tura (2006)
3.4	composed, Gd, $Gd_{0.85}Er_{0.15}$	LTSC, 5 T	displacer	helium gas	0.85	–	Arnold et al. (2011)
3.5	composed, Gd, $Gd_{0.74}Tb_{0.26}$, $Gd_{0.85}Er_{0.15}$	LTSC, 2 T	displacer	helium gas	0.2 – 1.2	2.5	Tura (2005)

4. AMR working body

Literature data analysis (see Tables 1–4) shows that gadolinium and its alloys with terbium, dysprosium, erbium, and yttrium are mainly used in currently existing prototypes of magnetic refrigerating machines operating in room temperature area. Compositions based on lanthanum-ferrum-silicon intermetallic compound are applied in several prototypes, and in one prototype - $Pr_{0,65}Sr_{0,35}MnO_3$ manganite (Legait et al., 2014).

Today lanthanum-ferrum-silicon-based compounds ($La(Fe_{13-x}Si_x)$) are considered to be quite promising from the point of view of their application in magnetic refrigerating machines operating in the room temperature range (GschneidnerJr et al., 2005). $Gd_5(Si_{1-x}Ge_x)_4$ and $MnFe(P_{1-x}As_x)$ compounds are also promising (GschneidnerJr et al., 2005). However, these materials have the first-order magnetic phase transition; such materials reveal hysteresis both in field dependences of magnetization and changes of the magnetic part of entropy ΔS_M (H). Nevertheless, it is important to note that work is underway to obtain such alloys with partial substitution of elements (Fu et al., 2018; Gębara et al., 2017), which can lead to a change in the mechanisms of transition and reduce the hysteresis value. For example, such materials as La(FeSiCo)H that are only slightly into the first order transition regime have been proposed (Fu et al., 2018), and that's why these materials can have very small hysteresis. Hysteresis in M(H) causes additional heating due to hysteresis loss, and hysteresis in ΔS_M (H) – cycle equilibrium disturbance. These both processes degrade refrigerating machine performance. Therefore, materials with the first-order phase transition are undesirable to be used as working body of magnetic heat machines. In addition, the technology of manufacturing such materials is quite difficult, and the materials themselves possess high hardness and brittleness, which makes difficult their processing in order to have them in the form needed for their use in magnetic refrigerators. In the course of magnetic refrigerating machine usage brittle materials will crumble, and their highly hard particles will be carried away by heat carrier flow and get into valves and pump leading to their rapid wear. To prevent this effect, brittle materials are coated with protective polymer film, but such coating deteriorates heat exchange between the material and heat carrier bringing to nothing the advantages of the applied compounds. It is worth noting that the magnitude of the heat transfer blockage can be decreased by reducing the thickness of polymer coating.

Currently, magnetocaloric effect in manganites, including $Pr_{1-x}Sr_xMnO_3$, is rather intensively investigated (GschneidnerJr et al., 2005). At the same time it should be noted that this system does not feature essential values of magnetocaloric effect (anyhow, it does not exceed that observed in gadolinium) (Chen et al., 2000; Chen and Du, 2001) though the second-order magnetic phase transition takes place in it; so, application of $Pr_{0,65}Sr_{0,35}MnO_3$ compound by the authors of (Legait et al., 2014) is reasoned most likely by research interest. In addition, manganites are ceramics having high hardness, so they have the above-mentioned disadvantages typical for very hard and brittle materials.

5. Heat carrier transfer system

Data provided in Tables 1–4 show that both liquids and gases are used as a heat carrier in AMR heat machines operating in the range of room temperature values. Most often water as well as water-based mixtures (water – ethyl alcohol, water – antifreeze, water–ethylene glycol) are used as a liquid. If the device is designed to be operated at below 0 °C temperature, additives are used to decrease water freezing temperature. Anticorrosive additives were also added to water to prevent working material oxidation (1% water solution of caustic (NaOH) was used for this purpose in Cheng et al. (2013)). Besides water, oils were also used – silicone and olive.

Liquid provides quite good thermal contact with magnetic material surface in regenerator and hence high heat transfer factor between heat carrier and magnetic material necessary for the efficient operation of regenerator and heat machine as a whole. It was noted in (Kitanovski and Egolf, 2010) that liquid metals have maximum heat-transfer factor for metal surface – liquid system. Due to this fact it was suggested to use them as a heat carrier in AMR heat machines. It should be noted that the only metal being in liquid state at room temperature is mercury (melting temperature is −38.8 °C), however due to its extreme toxicity practical use of this substance is rather difficult. Currently, intensive research in the field of the development of nanoliquids containing nanoparticles

Table 3
Data of the prototypes of back-and-forth AMR magnetic heat machines on permanent magnets (PMS – (field) source on permanent magnets) (Balli et al., 2012; Cheng et al., 2013; Clot et al., 2003; Czernuszewicz et al., 2014; Dupuis et al., 2009; Engelbrecht et al., 2009, 2011; Kawanami et al., 2006; Kim and Jeong, 2009; Legait et al., 2014; Romero Gómez et al., 2013; Sari and Balli, 2014; Tagliafico et al., 2009; Tagliafico et al., 2013; Trevizoli et al., 2011; Tušek et al., 2012; Tušek et al., 2013, 2014; Yao et al., 2006; Zheng et al., 2009).

No.	Regenerator material	Magnetic field source type, generated magnetic field strength	Heat carrier transfer system	Heat carrier	Operating frequency of the device, Hz	Field rate of change, T/s	Reference
1	Gd, 0.6 mm particles	PMS, 1 T	–	water	0.35	–	Kawanami et al. (2006)
2	Gd, particles	PMS, 1.5 T	displacer	helium gas	1	–	Yao et al. (2006)
3	La–Fe–Co–Si–B, 0.42 to 0.85 mm particles	PMS, 1.5 T	displacer	1% aqueous solution of caustic	0.9	–	Cheng et al. (2013)
4	Gd	PMS, 1.5 T	pump	–	–	–	Zheng et al. (2009)
5	Gd, 1 mm thick plates, distance between plates 0.15 mm	PMS, 0.5 T	pump	water	0.42	–	Clot et al. (2003)
6	Gd, 1 mm thick plates	PMS, 0.8 T	–	–	1	–	Dupuis et al. (2009)
7	1. Gd, 1 mm thick plates, distance between plates 0.3 mm; 2. Pr–Sr–Mn–O, 1 mm thick plates, distance between plates 1 mm; 3. La–Fe–Co–Si, 1 mm thick plates, distance between plates 1 mm	PMS, 0.8 T	–	–	0.1 to 1.43	–	Legait et al. (2014)
8	1. Gd, 0.9 mm thick plates, distance between plates 0.5 mm; 2. La–Fe–Co–Si, 0.9 mm thick plates, distance between plates 0.5 mm	PMS, 1.03	–	water - antifreeze	–	–	Engelbrecht et al. (2009)
9	1. Gd, 0.25 mm thick plates, distance between plates 0.25 mm, cylindrical particles (2.5 mm diameter, 4 mm long), 0.35 to 0.5 mm spherical particles; 2. La–Fe–Co–Si, 0.5 mm thick plates, distance between plates 0.2 mm	PMS, 1.15 T	displacer	water - antifreeze	0.1 to 0.45	2.5 to 3.5	Tušek et al. (2014), (2013), (2012)
10	Gd, 0.3 mm powder	PMS, 1.5 T	pump	water - antifreeze water- ethyl alcohol	0.2	–	Tagliafico et al. (2009), (2013)
11	Gd, 1 mm thick plates	PMS, 1.45 T	pump	silicone oil	0.5	–	Balli et al. (2012), Sari and Balli (2014)
12	Gd, 0.325 to 0.5 mm particles	PMS, 1.58 T	–	helium gas	1	–	Kim and Jeong (2009)
13	Gd, 0.85 mm thick plates, distance between plates 0.1 mm	PMS, 1.65 T	displacer	water	0.14	–	Trevizoli et al. (2011)
14	Gd, 2 to 5 mm particles	PMS, 1 T	pump	ethylene glycol	0.025	0.2	Czernuszewicz et al. (2014)
15	Gd, 0.5 mm thick plates, distance between plates 0.25 mm	PMS, 1	pump	water	0.08	0.4	Romero Gómez et al. (2013)

of various substances is carried out, including nanotubes (Saidur et al., 2011). Such liquids feature increased heat conductivity and heat-transfer factors in comparison with traditional liquids used as heat carriers. In particular, it is reported that adding of 0.4% fraction of nanoparticles to initial liquid can increase its thermal conductivity by 40% (Saidur et al., 2011). So, usage of nanoliquids in AMR heat machines as a heat carrier should be recognized to be promising.

As it follows from Tables 1–4, besides liquids used as a heat carrier in AMR heat machines there are also applied gases – nitrogen and helium, the latter is used most often. It should be noted that gases are used at sufficiently high pressures–up to 10 atm, because of their low heat capacity and heat transfer at atmospheric pressure; so, use of gases assumes additional technical difficulties connected with high pressure. Therefore, use of water-based liquids and water solutions of antifreeze substances should be acknowledged to be preferable.

As it can be seen from data given if Tables 1 through 4, two types of devices are applied to generate heat carrier flow through the AMR heat machine operating loop: displacer and circulating pump. Displacer is a plunger that is mechanically moved using a rod in the cylinder divided by the plunger into two parts. Today the displacers are broadly used in cryocoolers. The advantage of the displacer is high speed of operation and the possibility to arrange AMR heat machine based on the scheme without any additional switching valves decreasing the reliability of the device as a whole and leading to extra heat losses. At the same time essential disadvantage of the operating scheme of AMR heat machine with displacer is some “dead volume” of heat carrier that constantly exists in the regenerator while the machine operation and thus does not participate in heat exchange processes in hot and cold heat exchangers. Presence of such a dead volume can essentially decrease the efficiency of the device as a whole. There is no such disadvantage for the schemes where heat carrier is transferred along the loop in one direction by a pump, and flow switching during operation cycle is implemented using flow direction valves.

6. Magnetizing–demagnetizing of a working body

Magnetic heat machines can be divided into two groups as to the method of magnetizing–demagnetizing of the working body. The first group includes the devices where magnetization (demagnetization) of the working body is implemented by placing the working body into the operating gap of the magnetic system (taking out of the working body from the operating gap of the magnetic system). The second one – the devices where

Table 4
Data on prototypes of rotational AMR magnetic heat machines (PMS – (field) source on permanent magnets) (Aprea et al., 2014; Arnold et al., 2014; Bahl et al., 2014; Bohigas et al., 2000; Engelbrecht et al., 2012; He et al., 2013; Jacobs et al., 2014; Lozano et al., 2014; Lozano et al., 2013; Okamura et al., 2007a, Okamura et al., 2005; Shir et al., 2005; Tura and Rowe, 2011, 2009b, 2007a; Tušek et al., 2010; Vasile and Muller, 2006; Vasile and Muller, 2005; Zimm et al., 2007, 2006; Zimm et al., 2005).

No.	Regenerator material	Magnetic field source type, generated magnetic field strength	Heat carrier transfer system	Heat carrier	Operating frequency of the device, Hz	Field rate of change, T/s	Reference
1	1. Gd, 0.425 to 0.5 mm particles; 2. Gd–Er, 0.25 to 0.355 mm particles	stationary PMS, 1.5 T	pump	water	4	–	Zimm et al. (2006), (2005)
2	Gd, powder	PMS, 2 T	displacer	helium gas	0.04	1 T/s	Shir et al. (2005)
3	Gd, plates	rotational PMS, 1.5 T	–	–	2	–	Zimm et al. (2007)
4	La–Fe–Si–H, 0.177 to 0.246 mm particles (multilayer)	rotational PMS, 1.5 T	pump	water - antifreeze	4	–	Jacobs et al. (2014)
5	Gd, foil	stationary, 0.95 T	pump	olive oil	0.33	–	Bohigas et al. (2000)
6	Gd-Y, Gd-Dy, 0.6 mm spherical particles (multilayer)	rotational, 0.77 T	–	water	3.33	–	Okamura et al. (2005)
7	Gd, 0.5 mm spherical particles	rotational, 1.1 T	–	water	3.33	–	Okamura et al. (2007)
8	Gd, Gd–Tb, plates	rotational, 0.98 T	–	–	4	–	Vasile and Muller (2006), (2005)
9	Gd, 0.3 and 0.6 mm particles	rotational, 1.47 T	displacer	water	1.4 - 5	–	Tura and Rowe (2009), (2007)
10	Gd, 0.5 mm spherical particles	rotational, 1.54 T	displacer	water - ethylene glycol	0.5 – 0.8	–	Arnold et al. (2014)
11	Gd, 1 mm thick plates	rotational, 1.5 T	pump	helium	1.5	–	He et al. (2013)
12	Gd, 0.25 mm thick plates	stationary, 0.98 T	pump	water	0.25 - 4	–	Tušek et al. (2010)
13	Gd, 0.25 to 0.8 mm spherical particles	stationary, 1.24 T	pump	water – ethylene glycol; water - antifreeze	1.5 - 10	–	Bahl et al. (2014), Engelbrecht et al. (2012), Lozano et al. (2014), Lozano et al. (2013)
14	Gd, 0.4 to 0.5 spherical particles	rotational, 1.25 T	pump	water	0.72	–	Aprea et al. (2014)

magnetization–demagnetization is implemented by switching on/off of current in the magnetic field source winding (the working body itself rests here). In the first group, placing of the working body into the area of exposure to magnetic field can be executed either by the field source movement (here the working body rests), or by the working body moving (here the field source rests).

6.1. Switching operation mode of a superconducting field source

The method where magnetization-demagnetization is provided by means of switching the current in the magnetic field winding with the rest (stationary) working body was applied in magnetic refrigerating devices operating based on Carnot magnetic cycle in the range of cryogenic temperatures below 20 K–such devices are called refrigerators with adiabatic demagnetization (AD refrigerators). Fig. 3 depicts AD refrigerator general block diagram. The device consists of a switched magnetic field source that is a superconducting solenoid made of a low-temperature superconductor (LTSC) and two thermal valves that provide thermal contact at isothermal segments of Carnot cycle with cooled heat load and heat sink and isolating the working body at the segments corresponding to adiabatic magnetization and demagnetization. Such scheme was implemented, in particular, in Hakuraku and Ogata (1985), where a superconducting Nb–Ti solenoid was used to generate the field of 3 T intensity. Solenoid operated in pulse mode and provided 0.3 Hz operating frequency of the device. And the average rate of field build-up was of about 3.8 T/s, maximum value at the initial segment was about 9 T/s. LTSC solenoid was used in AD refrigerator suggested in Bézaguet et al. (1994). Solenoid provided maximum field strength of 3.5 T at the average rate of field increase/decrease while magnetizing/demagnetizing of 17.5 T/s. Considerably less field rates of change were used in AD refrigerator in

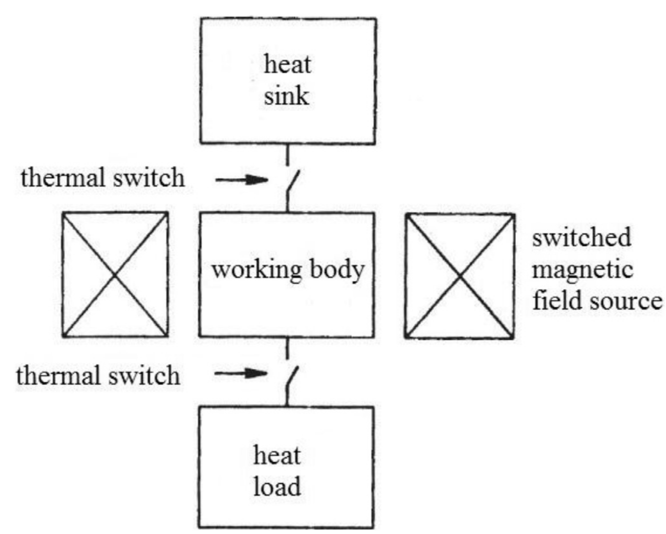

Fig. 3. General block diagram of a magnetic refrigeration device with a stationary working body and switched magnetic field source operating based on Carnot magnetic cycle (AD refrigerator).

Kashani et al. (1996), where LTSC solenoid with maximum field of 6.5 T provided field change while remagnetization at the average rate of 0.04 T/s, and the complete AD refrigerator cycle achieved 690 s. Low value of the field rate of change (0.07 T/s for maximum field value of 2 T) generated by LTSC superconducting solenoid was used in AD refrigerator in (Bartlett et al., 2015).

Switching operation mode of a superconducting field source in AMR heat machine was used in (Blumenfeld et al., 2002b; Green et al., 1990). An LTSC-based field source was used in

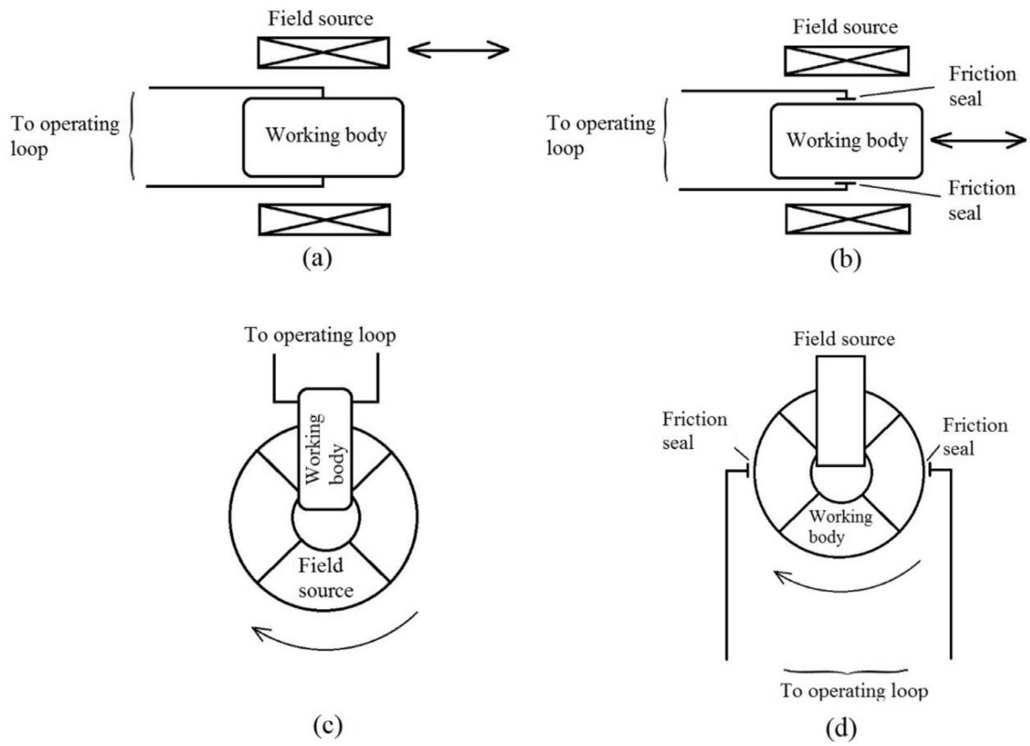

Fig. 4. Magnetic heat machines with magnetizing–demagnetizing by means of moving working body (regenerator) and magnetic field source: (a) machine with stationary working body and linear movement of magnetic field source; (b) machine with stationary magnetic field source and linear movement of working body; (c) machine with stationary working body and rotational movement of magnetic field source; (d) machine with stationary magnetic field source and rotational movement of working body.

Green et al. (1990), and HTSC-based one was used in Blumenfeld et al. (2002b). LTSC field source was cooled by liquid helium and generated 7 T in the operating gap. Field build-up rate in the source was 0.23 T/s, magnetization/demagnetization time was 30 s at complete AMR cycle length of 70 s. HTSC source used in Blumenfeld et al. (2002b) had a warm operating gap of 2.5 cm diameter and of 15.5 cm length, where 1.7 T field was generated. A superconducting solenoid contained 1870 turns of HTSC Bi-2223 type conductor (total wire length was 624 m, winding was divided into 17 binary sections); its external diameter was 18 cm, and the inner one was 5 cm. Lead-in wires were made of BSCCO material and rated for 200 A current at the operating current of solenoid of 100 A. The solenoid was powered from a controlled current source with maximum current of 350 A. A two-stage Gifford-McMahon cryocooler was used to refrigerate the field source, which high-temperature stage maintained the solenoid heat shield and current lead at 80 K temperature, and the low-temperature stage maintained the solenoid at 40 K temperature. The rate of field rise in the operating gap of the field source was about 0.2 T/s, which defined the field rise/decrease time–8 s at the total length of AMR cycle of 30 s. Table 1 gives the parameters of AMR heat machine with stationary switched superconducting field sources from Blumenfeld et al. (2002b), Green et al. (1990).

In Heer et al. (1953), an electromagnet with maximum field in the operating gap of 0.95 T was used as electrically switched magnet field source. There was no data on the field rate of change provided, but as one operation cycle of the device was 190 s it can be assumed that the field rate of change did not exceed several hundredths of T/s. There was no data revealed in available literature on other magnetic refrigerating machines with switched electromagnet as a magnetic field source.

It should be noted that application of electromagnets is possible only in laboratory devices, since essential fields in such field sources can be reached only with high power inputs and at considerable weight and size parameters. For instance, laboratory electromagnet FL-1 weighs 900 kg at 420 × 625 × 1160 mm overall dimensions, and consumes 3 kW at magnetic field strength of 1 T in a 2 cm wide operating gap. In addition, electromagnets feature essential inductivity due to the presence of magnetically soft magnetic conductor that makes it impossible to reach high rates of field change, and hence provide high operating frequency of the heat machine needed to achieve high refrigerating capacity values.

6.2. Magnetic field change in a working body: motion of a working body or a field source

The next group of magnetic heat machines includes the devices where magnetization/demagnetization is implemented by placing/taking out of magnetic working body (regenerator) to/from the area of exposure to magnetic field source. Such devices can be implemented by two methods:

– working body rests (stationary working body), field source moves relative to the working body (Fig. 4a and c);
– field source rests (stationary field source), working body moves relative to the source (Fig. 4b and d).

Two types of movement are possible in both cases:

- linear (back-and-forth motion), when the field source or the working body executes periodic linear motion along a certain direction (Fig. 4a and b);
- rotational, when the field source or the working body executes rotational movement (Fig. 4c and d).

6.2.1. Linear motion of a working body and a stationary magnetic field source: examples

Superconducting field sources require cooling of solenoid winding to cryogenic temperatures (4.2 K for LTSC and 40 K and higher for HTSC) that is provided either using cryogenic liquids or cryocooler (sometimes cryocooler is used in closed cooling systems in combination with cryogenic liquids). A cryostat is required in both cooling methods for thermal insulation of the cooled solenoid from the environment. So, a superconducting field source with a refrigerating system is quite a bulky device which it is rather difficult to move especially when it is rotational movement (difficulties grow if cryogenic liquid is used for cooling). The analysis of data on magnetic heat machines available in literature (Arnold et al., 2011; Hirano et al., 2002; Kitanovski et al., 2015; Kulkarni, 2015; Richard et al., 2004; Rowe and Tura, 2006; Rowe and Barclay, 2002; Tura, 2005; Yu et al., 2010; Zimm et al., 2018, 1998) and patent bases showed that the superconducting sources are not used in the machines with a moving field source. Stationary superconducting field sources have also not yet been used in the machines based on turning (rotational) schemes. Thus, the superconducting field sources are currently applied only in the magnetic heat machines built based on the scheme of the linear back-and-forth motion of the working body (regenerator) with a stationary field source.

Several AMR magnetic heat machine prototypes implemented based on linear back-and-forth motion of regenerator and stationary superconducting magnetic field source are described in literature (Arnold et al., 2011; Hirano et al., 2002; Richard et al., 2004; Rowe and Tura, 2006; Rowe and Barclay, 2002; Tura, 2005; Zimm et al., 1998). Table 2 provides their data.

As it can be seen, all these devices operate based on LTSC magnetic field sources generating magnetic field from 2 to 5 T, and the field rate of change is by one order higher than in the case of switched superconducting field sources used in AMR heat machines (see Table 1). In fact, the devices of 3 kinds are presented in Table 2, since the devices numbered 3.1 through 3.5 are the versions of the same schematic design machine. In the first two devices (numbers 1 and 2 in Table 2) the back-and-forth motion is provided by linear drive units – pneumatic and hydraulic ones, respectively, while in the third device – by a crank-and-rod mechanism.

Fig. 5 depicts the block diagram of AMR heat machine described in (Zimm et al., 1998). The machine includes a stationary magnetic field source with a warm operating gap based on LTSC (Nb–Ti) cooled by liquid helium, a pneumatic linear drive, the system of switching the direction of heat carrier flow, a pump, cold and hot heat exchangers, composed regenerator (R1 and R2), and a pipeline connecting all the machine components and forming its operating loop where heat carrier circulates. A composite regenerator is used in this work that includes two identical containers that are by turns placed into the working gap of the field source. Such an approach enables to compensate partially the force needed to remove the regenerator from the field source. In particular, while removing R1 regenerator from the operating gap of the field source when moving upward, R2 regenerator that becomes exposed to the field source impact will be drawn into it under the effect of ponderomotive forces that will at the same time hinder R1 regenerator from being removed from the operating gap. So, ponderomotive forces acting on R1 and R2 will be partially compensated decreasing the force that the drive must provide in the course of the device operation and reducing the power consumed by the drive.

It is possible to optimize the effect of ponderomotive forces by means of selection of a distance between the containers. Besides compensation of ponderomotive forces, the scheme with the composite regenerator including two containers which dimensions fit the operating gap of the magnetic field source enables to double refrigerating capacity versus a single-container regenerator scheme. Each of the containers of AMR machine (Zimm et al., 1998) contained 1.5 kg of spherical gadolinium particles of 0.15 to 0.3 mm diameter; and maximum force gained by the drive when moving regenerators was 2500 N. Field rate of change while remagnetization was about 5 T/s.

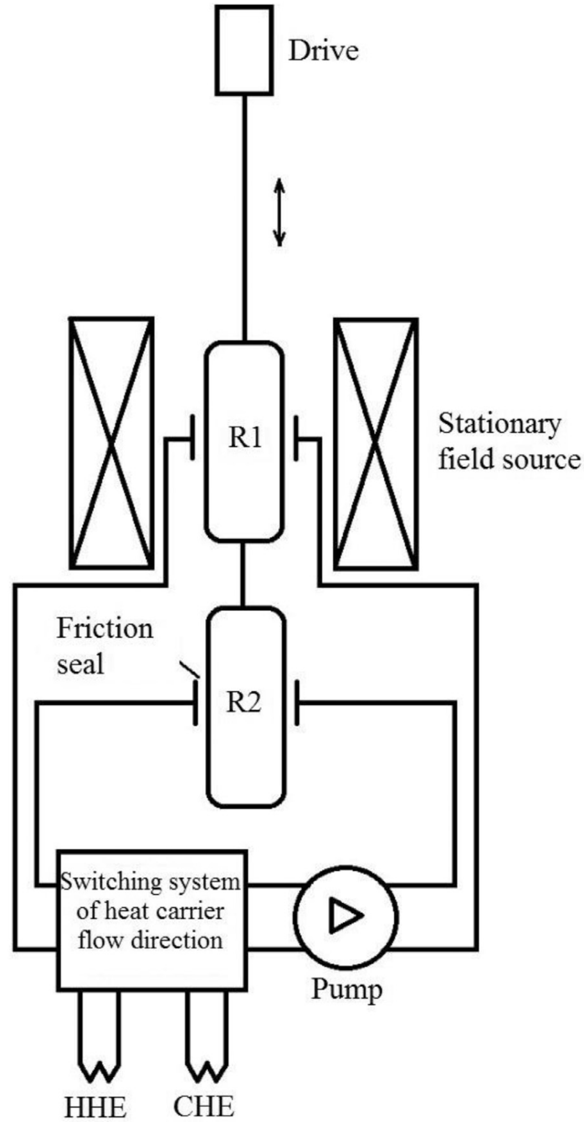

Fig. 5. Block diagram of AMR heat machine presented in (Zimm et al., 1998).

AMR heat machine suggested in Hirano et al. (2002) was of approximately similar design. The device also used a composite regenerator consisting of two containers (8 cm long, of 6.2 cm inner diameter) each of that contained 1.1 kg of spherical gadolinium particles of 0.3 mm diameter moved by a hydraulic linear drive. Magnetic field of 4 T value was generated by LTSC magnetic field source with a warm operating hole of 10 cm diameter cooled by contact method using Gifford-McMahon cryocooler. Maximum force while moving regenerators was 1600 N.

Unlike the above-mentioned machines from Hirano et al. (2002), Zimm et al. (1998), the back-and-forth motion in AMR heat machine described in Richard et al. (2004), Rowe and Tura (2006), Rowe and Barclay (2002) was provided using an electric motor-driven crank-and-rod mechanism – Fig. 6.

A magnetic field source was designed based on a solenoid made of LTSC Nb–Ti wire (solenoid inductance was 105 H), which temperature is maintained at the level of 4.2 K by the contact method using Gifford-McMahon cryocooler. The solenoid was placed into a vacuum cryostat. Current leads were made of HTSC. The field rate of change while magnetization-remagnetization was 2.5 T/s. The dimensions of one regenerator were as follows: 2.5 cm diameter, 8.8 cm length.

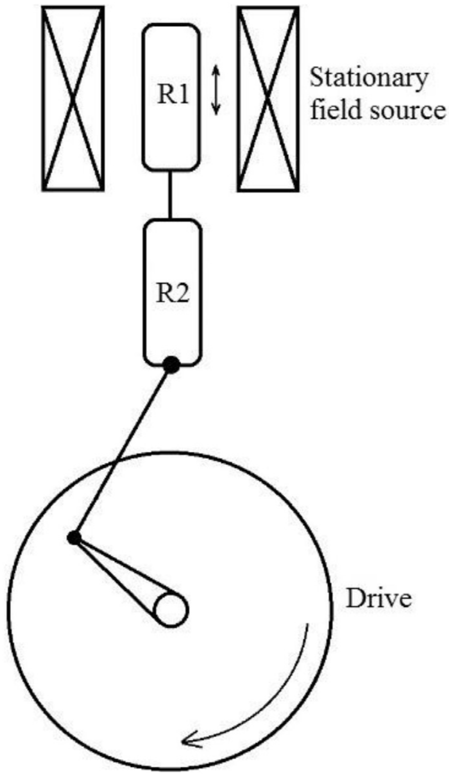

Fig. 6. Block diagram of back-and-forth AMR heat machine with a crank-and-rod mechanism.

The majority of back-and-forth AMR heat machines are the devices with magnetic field sources designed based on permanent magnets (Allab et al., 2006; Balli et al., 2012; Bouchekara et al., 2012; Bour et al., 2009; Cheng et al., 2013; Clot et al., 2003; Czernuszewicz et al., 2014; Dupuis et al., 2009; Engelbrecht et al., 2009, 2011; Hirano et al., 2009; Kawanami et al., 2006; Kim and Jeong, 2009; Legait et al., 2014; Lu et al., 2005; Romero Gómez et al., 2013; Sari and Balli, 2014; Tagliafico et al., 2009; Tagliafico et al., 2013; Trevizoli et al., 2011; Tušek et al., 2013; Tušek et al., 2014; Yao et al., 2006; Zheng et al., 2009). Technical characteristics of some of them are provided in Table 3.

6.2.2. *Rotational motion of a working body or a magnetic field source: examples*

One more large group of AMR heat machines are those with turning (rotational) movement of field source or working body (turning (rotational) AMR heat machines) (Aprea et al., 2014; Arnold et al., 2014; Bahl et al., 2014; Bohigas et al., 2000; Engelbrecht et al., 2012; He et al., 2013; Jacobs et al., 2014; Lozano et al., 2014; Lozano et al., 2013; Okamura et al., 2007, Okamura et al., 2005; Shir et al., 2005; Tura and Rowe, 2011, 2009b, 2007a; Tušek et al., 2010; Vasile and Muller, 2006; Vasile and Muller, 2005; Zimm et al., 2007, 2006, 2005). Technical characteristics of some of them are provided in Table 4.

As it can be seen, operating frequencies of the devices on permanent magnets are within the same range as for the machines with superconducting magnet field sources: 0.025–1.5 Hz. Field rates of change in the permanent magnet-based devices are within the range from 0.2 to 3.5 T/s, which also agrees with the values for the devices with superconducting field sources (0.2 to 5 T/s, see Tables 1 and 2). And the devices with permanent magnets are built both based on the scheme with stationary magnet field source and with stationary regenerator. The latter ones are possible in the case of permanent magnet-based sources due to the

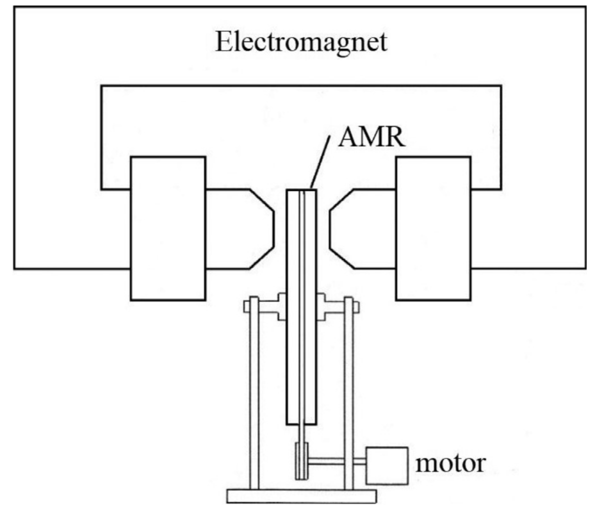

Fig. 7. Block diagram of rotation AMR heat machine with electromagnet.

compactness of such sources. It should be noted that field sources based on permanent magnets are characterized by less field values in operating gaps – as it can be seen from Table 3, maximum field value does not exceed 1.65 T. In addition, high fields in the permanent magnet-based sources can be generated only in rather narrow operating gaps (Bjørk et al., 2010). In particular, operating gap of the magnetic field source with maximum magnetic field strength (1.65 T) among those considered in Table 3 is 1 cm. Less volume of working material can be placed into narrow gaps, which leads to less refrigeration capacity values at the same values of operating frequency.

Table 4 shows that in rotational AMR heat machines both stationary and rotating field sources based on permanent magnets are used (field sources or regenerators in rotational AMR heat machines are electric motor driven), and the field in the operating gap of the source does not exceed 2 T (is within 0.77 to 2 T interval). At the same time operating frequency of such machines is higher than that of the back-and-forth devices (0.25 to 10 Hz versus 0.025 to 1.43 Hz, see Table 3), which provides their higher efficiency (Yu et al., 2010).

The analysis of available literature revealed neither rotational-type device with superconducting magnetic field source used. At the same time, a rotational-type device with a stationary electromagnet as a magnetic field source was suggested in (Coelho et al., 2009). Fig. 7 shows the block diagram of the device.

It should be noted that an electromagnet is not an acceptable field source for magnetic heat machines since it consumes too much power to generate sufficient fields in the operating gap for the machine operation, and the operating gap remains here quite narrow. In particular, about 3 kW power is required to generate the field of about 1.5 T in about 2 cm gap.

7. Conclusions

Use of superconducting magnetic system (SMS) as a magnetic field source for a solid-state magnetic heat pump provides a number of advantages. It can be stated that currently the niche of SMS-based magnetic heat machines remains poorly developed, and new technical solutions that do not require the development of sophisticated devices but at the same time enable to extend essentially the range and capacity of refrigeration are of great practical interest.

The most optimal ways of magnetization–demagnetization are the following: switching of operating current in the winding of the magnetic field source and mechanical moving of regenerator with working body relative to the operating gap of the field source. In the latter case the motion can be implemented both as linear (back-and-forth version of the device) and rotational (rotational version of the device).

Transfer of heat carrier in the operating loop of the machine is provided as a rule using circulation pump. This allows preventing emergence of heat carrier “dead volume” that does not leave the regenerator, does not participate in heat exchange process, and degrades the device performance. Water-based solutions and suspensions with additives decreasing corrosive properties of water and improving its heat exchange characteristics are used as a heat carrier.

Heavy rare-earth gadolinium metal and its alloys with dysprosium, terbium, and erbium can be used as a working body. These metals posses good mechanical properties (first of all, plasticity), which allows producing working body of different forms – powders, spherical particles and plates, and within a wide range of dimensions, which is necessary to optimize operating parameters of active magnetic regenerator. In addition, usage of gadolinium alloys with other heavy rare-earth metals in regenerator will make it possible to provide the most efficient temperature profile of magnetocaloric effect inside this component of the heat machine.

Regenerator is implemented in the form of a cylindrical container in case of a shuttle-type machine, and in the form of a sectional wheel for a rotation-type machine. And both single-container and double-container regenerator versions are used for the reciprocating machine, and two-sectional or multi-sectional versions–for the rotation machine.

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