SURVEY

WORK ON HEAT PIPES IN EUROPE

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This paper gives a survey of the work done in Europe on heat pipes. The substance of this survey is based in large measure on the reports presented at the First International Conference on Heat Pipes, held at Stuttgart in 1973.

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ABBREVIATIONS

R — research; FT — fundamental theory; FE — fundamental experimentation; AP — analysis and operation of heat pipes; C — consistency; A — applications: AT — at ground conditions; AC — in industry, manufacturing of heat pipes; AS — in space vehicles.

Assumed Classification of Types of Heat Pipes Based on Their Operating Temperature Range

Cryogenic heat pipes: $T < \sim 200°K$; low-temperature heat pipes: $\sim 200°K < T < \sim 550°K$; heat pipes for the moderate temperature range: $\sim 550°K < T < \sim 750°K$; high-temperature heat pipes: $T > \sim 750°K$ (high-temperature heat pipes operating only in an inert atmosphere: $T > \sim 1{,}400°K$).

Belgium

SABCA (Brussels): A (AT, AC, AS). Flexible small-diameter ammonia heat pipes have been developed. The wick is made in the form of a stainless steel mesh. The length of the pipes is 1 m, and the inner diameter is 3.2 mm. The transferred power is more than 10 W in the temperature range from −20 to +80°C in a horizontal position and a 5-mm negative inclination. The temperature drop for a 10-W thermal load is less than 4° at a distance of 5 mm from the heater and 20 mm from the ends of the heat pipe. The weight of the heat pipe is 33 g.

Belgian designers have also developed heat pipes with inner diameters of 6.4 mm and 12.8 mm, which can also be used at ground or space conditions.

Czechoslovakia

State Research Institute of Machine Construction (Bechovice near Prague)* R (AP), A (AT). An extensive program has been worked out for research and development of heat pipes with liquid-metal coolants. The metals used are mercury, potassium, and sodium. The heat pipes have mesh wicks. In heat pipes with longitudinally cut grooves the coolant used was sodium. The main purpose of the work done was to investigate the limiting heat fluxes transferred to the heat pipes.

Theoretical and experimental work was done on the investigation of centrifugal heat pipes for the cooling of electrical machinery. The hollow shaft of a two-pole asynchronous electric motor of the enclosed type (output power 10 kW, v = 1,800 rpm) was used as a centrifugal heat pipe. The thermal

*The information used here is taken from the reports presented by members of the State Research Institute at the First International Conference on Heat Pipes, held at Stuttgart.

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resistance of the shaft was reduced by a factor of 10, and the heat flux from the stator to the rotor was considerably increased, resulting in a substantial reduction in the temperature of the stator winding (by approximately 14°K). The temperature in the rotor winding was reduced by about 33°K.

For the cooling of high-speed copper circuit breakers, ribbed copper heat pipes with water coolant were developed (length of pipe L = 115 mm, inner diameter d = 28 mm, transferred power Q = 150-250 W); these reduce the temperature of the moving contact by 44°K and the temperature of the fixed contacts by 33°K.

Federal Republic of Germany

Brown Boveri and Company (BBC) (Heidelberg): R (FE*, C*), A (AT, AC, AS*). Heat pipes made of Nb — 1% + Zr, with cesium and sodium coolants, have been developed for cooling the collectors of thermionic converters.

Prolonged resource tests were performed on one cesium and one sodium heat pipe (length L = 400 mm, inner diameter d = 10 mm, 64 grooves along the axis: 0.25 mm wide and 0.4 mm deep). The heat pipes operated in a gravitational field at 1,100°K when there was a heat flux of Q ~ 60 W/cm^2 at the evaporator. After operating for 1,600 h (Na) and 20,000 h (Cs), the heat pipes were found to have leaks at the evaporator weld. They were refitted and refilled with coolant. After 28,000 h of operation, the sodium heat pipe was found to have a large number of small openings in the evaporator. After this the pipe was refitted and again refilled with coolant. The experiments were stopped after 40,000 h of operation for the sodium pipe and 32,000 h for the cesium pipe.

In addition, sodium heat pipes with two collectors were tested together with thermionic converters for 32,000 h and 27,500 h, respectively, at T ~ 900°K and a heat flux of Q = 40 W/cm^2 at the collector.

Systems for cooling electronic instruments by means of heat pipes have been developed: a) a thermistor system (1,200 W, thermal resistance 0.035°K/W, rate of cooling of air v = 6 m/sec); b) an apparatus for portable current rectifier systems (700 W, thermal resistance 0.055°K/W, rate of cooling of air v = 6 m/sec).

Thermally regulatable heat pipes which maintain a constant temperature in the object being cooled have been developed.

Dornier: R (FE*, AP*, C*), A (AT, AS*). Dornier has developed a cryogenic heat pipe (length L = 25 cm, inner diameter d = 1 cm, pipe and meshes made of stainless steel, working liquid LN_2, maximum power 5 W, temperature drop 17°K, evaporator temperature 100°K).

Units for the desalination of seawater, using sun-heated heat pipes, have been developed. The heat pipes were made of aluminum. The wicks used were meshes made of stainless steel and saturated with various liquids. The working temperature of the pipes should be about 100°C. The first stage consisted in the development of a 20-m^2 unit, followed by one with a surface area of 400 m^2.

*Joint BBC/Dornier Development. Regulatable heat pipes were developed and manufactured. A handbook of data on heat pipes was prepared.

Joint BBC/Dornier Development: R (FE, AP, C), A (AS). Experiments were conducted with 28 different combinations of working fluid and heat-pipe shell material. Experimental investigations were conducted on the properties of capillary structures made of baked spherical particles and multilayer meshes; the properties included capillary pressure, permeability, and rate of evaporation of the liquid in the evaporator of the heat pipe.

Researchers developed an electrically insulated heat pipe with a ceramic structure in the adiabatic zone (the working fluid was a carbon compound of PPl with SF_6).

Prototypes of heat pipes capable of operating in outer-space conditions were constructed: an aluminum radiator (356 × 374 × 8.4 mm) with five flat aluminum heat pipes and an acetone coolant for cooling traveling-wave tubes (radiated power approximately 43 W, working temperature 5°C); a radiator with ten vapor chambers made of titanium, with water as with coolant (117 × 360 × 10 mm). The radiated power was 45 W at 73°C for water and 57°C for acetone.

A system of heat pipes used for cooling constant-current power converters was designed. It consists of four copper heat pipes which use water as the coolant and whose cylindrical evaporators are attached by

means of an epoxy resin to the mounting plate of a contact-current converter. Rectangular condensers are soldered to the base of a plate at an angle of 90° to the plane of the mounting plate. When the cooling device is at a working temperature of 50°C, the maximum temperature drop is less than 20°C. A honeycomb-type cold plate with eight aluminum heat pipes and acetone coolant (total power 150 W at about T = 30°C) is used as the refrigerating device.

The heat-pipe attachments (the junctions of the absorbing elements with the loop of the cooling device) are made of aluminum, and the coolant used is acetone (maximum power 150 W, evaporation temperature 35°C, temperature drop 7°C).

A regulatable aluminum heat pipe with feedback and an acetone coolant was developed. Helium is used as the noncondensing gas. The pipe has three integral slot-type ribbed radiators. The error in the maintenance of constant temperature is 1°C when the transferred power varies from 5 W to 60 W.

A system of heat pipes developed for the cooling of the solar batteries in the thermal module of the German AEROS satellite uses a heat pipe with chambers (an aluminum heat pipe with a cellular structure and an acetone coolant is connected to the solar batteries), an axial heat pipe, a titanium heat pipe with an artery and a standard coolant which passes through the shell of the satellite and is connected to a segmented heat pipe which has radiators (an aluminum heat pipe with a mesh and an acetone coolant). The total length of the system is about 85 cm, and the nominal transferred power varies from 10 W to 40 W. The total temperature drop is large because there are four bolts. The temperature drop in three heat pipes at approximately 30 W is 12 + 8 + 1 = 21°K.

Plans are being made for the use of an analogous system (without using a heat pipe with radiators) in which the heat sink will be a battery made of a material whose state of aggregation will be variable, for the launching of a meteorological rocket under the NASA research program.

Institut für Kernenergetik (IKE), University of Stuttgart, Institut für Kerntechnik und Energiewandlung (IKE e. V.) (Stuttgart): R (FE, AP, C), A (AT, AC, AS). Experimental investigations have been conducted on the various characteristics of heat-pipe wicks (baked powders of stainless steel and copper, a stainless steel mesh, and a phosphor-bronze mesh): capillary pressure, permeability, thermal conductivity under saturation conditions, maximum rate of evaporation of liquid from the wick. The coolant generally used was distilled water. An apparatus constructed for the measurement of thermal conductivity used heat pipes for isothermal heating and cooling.

Researchers have carried out an extensive program to investigate different variants of low-temperature coolants and structural properties of materials. Theoretical and experimental investigations were carried out on two-component heat pipes (the coolants used were mainly ethyl and methyl alcohol).

Various types (heat pipes with meshes, with grooves cut along the axis, plane and curved arteries, regulatable heat pipes with an artery, annular pipes) of cryogenic, low-temperature, and high-temperature pipes using mercury and alkali metals are being used in ground and space applications.

Work on the use of heat pipes in outer space is being conducted along the following lines.

1. The development of heat pipes made of copper, in which the coolant used is acetone (length 1 m, inner diameter 12 mm, length of evaporator 15 cm, length of condenser 15 cm; the design consists of six arteries, the transferred power is 100 W in a temperature range from −20 to 60°C, and the maximum temperature drop is 6°K).

2. Determination of the characteristics of flexible aluminum heat pipes with arteries made of stainless steel, in which the coolant used is ammonia (length 1 m, inner diameter 7 mm, length of evaporator 8 cm, length of condenser 8 cm), in a temperature range from 0 to 80°C. The limiting transferred power for these pipes (with a 5-mm inclination) was 55-60 W at 30°C and 35-40 W at 60°C. The maximum temperature drop was less than 5°K.

In May, 1974, somewhat modified heat pipes of this type, using ammonia and acetone as the coolant, were tested in the launching of a NASA meteorological rocket.

3. The development of an electrically regulatable heat pipe with feedback, made of stainless steel, in which ammonia is used as the coolant and which is used for regulating a prescribed variable temperature (25-45°C). The length of the pipe is 1,010 mm, the inner diameter is 10 mm, the reservoir length is 350 mm, and the inner diameter of the reservoir is 32 mm. The condensing gas used was argon. A large number of arteries were used in the pipe. The temperature control in this pipe was ±0.5°K (the on — off

dead zone of the regulator was ±0.3°K) when the power varied from 20 to 100 W and back. The deviation from the prescribed value was approximately 0.3°K (restoration time 4-5 min), and the deviation from the value actually obtained was approximately 0.2°K (restoration time 2 min). The power of the gas-reservoir heater was 10 W.

4. Development of an apparatus made of a material with variable phase state (PCM). The value of the accumulated energy was 50 W/h, the maximum heat input was 100 W, and the minimum melting time (or freezing time) of the PCM material was 4 h.

Octadecane (melting point ~28°C) was used as the material with variable phase state, and aluminum was used as the material for the wall and the porous filler.

5. Development of a system of heat pipes with variable conductivity for controlling the temperature of a microwave source.

The development of heat pipes used under ground conditions includes the development of standard low-temperature heat pipes used in heat exchangers and recuperators, for cooling electronic devices; centrifugal heat pipes in the form of a rotating drum (soft steel/diphenyl + diphenyl oxide) for the manufacture of plastic filaments and wires; plunger-type heat pipes made of stainless steel, using potassium as the coolant, for the manufacture of glass bottles; models of an absolutely black body on the basis of stainless steel heat pipes. The coolants used in these are potassium and sodium. In heat pipes made of Inconel the coolant used is sodium; the development of coaxial heat pipes used as components of pipe-type furnaces for creating isothermal conditions; assemblies (heat pipes made of stainless steel, using sodium as the coolant, and vapor chambers, thermal diodes, switchable heat pipes) used in heat-transfer and energy-accumulation systems in low-power energy converters (10-100 kW/h, operating temperature 600-800°C).

Kernforschungszentrum Karlsruhe (Karlsruhe): R. Theoretical and experimental investigations were conducted on heat pipes with an electrostatic pump. An electric field is used for pumping a liquid dielectric from the condenser into the evaporator. Tests were conducted on three heat pipes using nitrobenzene as the dielectric working fluid and having various types of design for the pumps and electrical condensers. The maximum transferred power as the result of the electrostatic pumping was 8 W, the maximum rise in the height of the liquid was 105 mm. The intensity of the applied electrostatic field was low (about 22 kV/cm), and the area of the cross section between the condenser plates was several tens of square centimeters. Good agreement between theory and experiment was observed.

France

Centre d'Etudes Nucléaires de Grenoble (Grenoble): R (FE, AP). Theoretical and experimental studies were carried out on heat pipes in which the coolants used were water, alcohol, and sodium; the main purpose of the investigations was to study the operating capacity of the heat pipes.

Centre National d'Etudes Spatiales (CNES) (Brétigny-sur-Orge): A (AS). Heat-pipe radiators for cooling semiconductor instruments were developed. The work was conducted by Société Nationale Industrielle Aérospatiale (Cannes, France), in conjunction with SABCA (Brussels, Belgium).

Société Nationale Industrielle Aérospatiale (SNIAS) (Cannes): A (AS). Radiators made of heat pipes manufactured by SABCA (Brussels, Belgium) are being constructed and investigated by SNIAS. The purpose of the research is to develop a system for cooling a 44-W semiconductor instrument used on board the French communications satellite "Symphonie." A conventional plane vertical radiator (weight 1.3 kg) and a plane vertical radiator made of a beryllium alloy (weight 1.1 kg) have been developed. Various plane and honeycomb-type radiators made up of heat pipes have been investigated. A plane radiator made of aluminum, with seven straight heat pipes, has been selected and classified. The weight of the radiator is 0.7 kg.

Sodernes (Suresnes): A (AT, AC). Coaxial heat pipes using alkali metals as the coolant have been developed. They are being used in industrial tube furnaces for creating isothermal conditions.

Great Britain

Ges-Marconi Electronics Ltd. (Chelmsford): R (FE, AP), A (AT, AS). Special features of the technology involved in manufacturing heat pipes for use in the electronics industry at low temperatures (—10 to +200°C) have been investigated.

The research program included the following:

1) manufacture of pipes and filling them with coolant;

2) experiments to determine the operating capacity of various heat pipes, some of which were constructed in laboratories and others at industrial plants. Tests were conducted to determine the operating capacity of stainless steel heat pipes using water, methyl alcohol, and ammonia as coolants. The main coolant chosen for the heat pipes was water;

3) theoretical calculations of characteristics on the basis of the data of computation programs set up in the laboratory;

4) experimental determination of permeability and radius of the capillaries of heat-pipe wicks, particularly flexible wicks, made of silica, in the process of evaporation of a liquid from them;

5) study of the possibilities of using heat pipes as experimental electronics equipment under ground conditions and outer-space conditions.

Hawker Siddeley Dynamics Ltd. (HSD) (Stevenage): A (AS). Investigations were carried out on various types of heat pipes for use on board satellites. Special attention was devoted to gas-regulatable heat pipes for thermostating electronic equipment with large power input.

Researchers developed aluminum heat pipes using ammonia with wicks made of a baked mesh of stainless steel and felt. A simple heat pipe with an inner diameter of 1.27 cm and a length of 66 cm and a regulatable heat pipe with an inner diameter of 1.27 cm and a length of 150 cm were constructed and tested. The regulatable heat pipe has a cold reservoir with a wick in which nitrogen is used as the noncondensing gas.

International Research and Development Co. Ltd. (IRD) (Newcastle upon Tyne): R (AP), A (AT, AS). Low-temperature pipes were developed for use under ground conditions in the electronics industry for cooling generator tubes, traveling-wave tubes, etc.

Heat pipes for use in industry and in everyday life were constructed.

Theoretical analysis and design work was done on heat pipes intended for use in computer engineering.

An aluminum heat pipe with an artery and a stainless steel mesh, using acetone as the coolant, was developed. The length of the pipe is 1 m, the length of the evaporator is 8 cm, the inner diameter is approximately 7 mm, the input power is 15-25 W, and the total temperature drop is approximately 4°K.

Researchers have developed a regulatable heat pipe with electrical feedback, in which the working fluid was water and the noncondensing gas was argon; the purpose of this pipe was to maintain the temperatures of electric heaters mounted in the evaporator at 70°C in the power range of 10 to 80 W. In order to make the heat sink small for small power output, another 15 W must be added. The maximum deviation of the prescribed temperature value was 7° upward and 9° downward, while the temperature of the evaporator was kept constant to within 1° for a period of 20 min.

National Engineering Laboratory (East Kilbride, Glasgow): A (AT). Investigations were conducted on heat pipes and thermosiphons when the temperature of the steam varied from 0 to 400°C. Heat pipes are used for evaporation by means of the waste heat of the fuel accumulated in the lower part of the carburetor of an internal-combustion engine in order to ensure uniform feed into the cylinders. This reduces the fuel consumption and generates more heat; it can be used for air heating in automobiles and industrial transport equipment, for recuperators used for recovering used heat, etc., and for drums used in rotating driers.

Attention is being given to the question of using steam-jet pumps for raising liquids at ground conditions, which makes it possible to place the boiler of a thermosiphon above the condenser.

Redpoint Associates Ltd. (Swindon): A (AT, AC). Production of various types of heat pipes used for cooling electronic equipment.

Royal Aircraft Establishment (RAE) (Farnborough, Hants): R (FT, FE, AP). Exact theoretical calculations are being carried out on the characteristics of heat pipes used on board spacecraft. An extensive survey on research concerning wick materials and wick systems has been carried out.

In order to correlate theory with practice, the RAE has constructed a large number of simple and gas-regulated heat pipes using acetone or ammonia coolants and various systems of wicks.

Simple heat pipes (length 2,000 mm, diameter 12.5 mm) were prepared, taking account of the requirements of spacecraft. Tests were conducted on a gas-regulated heat pipe using acetone (length 750 mm, diameter 12.5 mm) which had a dual wick with an artery. Tests will also be conducted on various specimens of gas-regulated heat pipes 1,000 mm long with various types of wicks. An attempt is being made to standardize the experimental conditions, in order to make it possible to make comparative measurements of the characteristics of the heat pipes.

Rutherford High Energy Laboratory (Didcot): A (AT). Application of cryogenic heat pipes to the cooling of targets on elementary-particle accelerators.

Signals Research and Development Establishment (SRDE) (Christchurch, Hants): A (AT). The heat-pipe research conducted at SRDE consists in determining the possibilities for using heat pipes to transfer heat in electronic instruments under ground conditions. The possibilities of heat pipes in such cases are evaluated by, conventional methods of research on conduction, convection, and radiation.

In order to obtain the range of working temperatures encountered in practice, the researchers worked with heat pipes using water, ammonia, and methyl alcohol as coolants. Various types of wicks are used in such heat pipes, for example, a uniform mesh, a mesh with a complex structure, wire wicks with arteries, and fiberglass.

Researchers at SRDE considered special types of heat pipes: electrical insulators of a flat plate, pipes of very small diameter, and various combinations of heat pipes with thermoelectric modules.

University of Reading (Reading): A (AT). Work included the development of heat pipes with liquid-metal coolant which are being used in nuclear engines and Stirling engines.

A stainless steel heat pipe with a mesh wick, using sodium as the coolant, 90 cm long and 2.5 cm in inner diameter, operated in a temperature range of 660-700°C with a power input of 1.2-1.4 kW.

Work was done to determine the possibility of using heat pipes with potassium and sodium as the coolant (the shell of the pipe was made of nickel and stainless steel), which could operate as heat pipes using a gas cushion for thermostating a radiation sensor (the shell of the pipe is made of stainless steel and holds a heat-generating element in the form of a thin rod, with a tube inner diameter of 9 mm and a tube length of 600 mm) at constant power, while the power level in a reactor may vary by a factor of 5 during the experiments.

Researchers also developed heat pipes with copper mesh, with water as the working liquid, which are used for cooling electronic systems.

University College of Swansea (Swansea): R (AP). Theoretical and experimental investigations were conducted on wickless centrifugal heat pipes. The length of the experimental heat pipe was 325 mm, the diameter of the outlet condenser was 30 mm, and the diameter of the outlet evaporator was 55 mm (angle of inclination 2°). Arkton 113, arkton 21, and water were used as the working fluids. The researchers determined the equivalent thermal conductivity of a heat pipe, which increases with increasing rotation rate, increasing mass of liquid input, and increasing applied thermal load.

University of Wales, Cardiff: A (AT). Investigations were conducted on the potential possibilities of using organic liquids as the coolants in heat pipes used in everyday life. These heat pipes are capable of transferring several kilowatts of heat in a horizontal direction to a distance of 3-4 m at a working temperature of about 300°C. The researchers considered heat pipes made of stainless steel or Thermax (a eutectic mixture of 73.5% diphenyl oxide and 26.5% diphenyl with various types of stainless steel meshes.

Euratom: R (FT, AP, C), A (AT). Theoretical studies were conducted on the hydrodynamics of a stream of vapor and liquid in heat pipes. The purpose of the research was to determine the maximum limitis of heat transfer (sonic limit, viscous limit).

Experiments were conducted to determine the limits of heat transfer along the axis in cylindrical heat pipes made of stainless steel with sodium as the coolant.

Capillary structures were developed for such heat pipes (effective diameter of pores 11 μ). The axial and radial (evaporator) heat fluxes were found to range up to 15.5 and 1.25 kW/cm^2. At low temperatures the data obtained confirm the theoretical calculations on the viscous limit of heat transfer. In the

range of temperature variation of the medium the data correspond to the theoretical calculations of the sonic limit of heat transfer. At high temperatures the critical heat fluxes lie considerably below the theoretical limit for the wicks, and points of overheating are found. It was concluded that these phenomena are probably caused by the presence of impurities.

Comparative investigations were conducted on heat exchange when sodium boils in heat pipes with a wick and when it boils in a large volume.

In the region of high-temperature pipes, an extensive experimental study was conducted on heat pipes made of lithium and silver. Recently experiments were conducted with three heat pipes (W — 26% Re/Li, 99.9%) at 1,600, 1,700, and 1,800°C and with two heat pipes (W — 26% Re/Li, 99.999%) at 2,000°C. It was found that the (W — 26% Re/Li) heat pipes are capable of operating for many years at 1,600°C. After one year of operation, the heat pipe exhibited considerable corrosion at 1,700°C, and at 1,800°C the pipe operated for only one month. It was found that (W — 26% Re/Ag) heat pipes can operate for 1,000 h at 2,000°C, although at that temperature there is considerable vaporization of the Re.

With regard to the low-temperature region, studies are being conducted on the operating regimes of heat pipes in which water is used as the coolant. Stainless steel heat pipes with water as the coolant have been investigated at high temperatures (~250°C). After only a few hours of operation, it was found that there was considerable generation of hydrogen in all the stainless steel heat pipes, which had been cleaned and pickled by different methods. No hydrogen generation was observed when a stainless steel heat pipe with a copper inner shell and a copper wick was operated for 10,000 h at 250°C. Consideration is being given to the possibility of using heat pipes operating at temperatures of 50-2,500°C for scientific and industrial purposes.

Netherlands

European Space Research and Technology Center (ESTEC) (Noordwijk): R (C), A (AS). Philips (Eindhoven): R (FT, FE), A (AT, AC). Extensive experimental and theoretical studies were conducted on the design of mesh wick structures, and the properties of these structures were determined (capillary pressure and stream resistance).

An apparatus was developed for measuring the thermal conductivity of multilayer superinsulating materials made of a foil, using a heat pipe with a gas cushion for isothermal heating and isothermal cooling under boiling conditions.

Experimental research was conducted on heat pipes using a gas cushion: heat pipes with a water coolant and with helium as the noncondensing gas, and heat pipes with a sodium coolant and with argon as the noncondensing gas.

Coaxial heat pipes which are used as isothermal sleeves in furnaces have been developed. The operating temperatures of the potassium heat pipes are ~450°C, and those of the sodium heat pipes range from 700 to 850°C. The operating temperature of specially designed sodium pipes is 1,150°C.

Analogous heat pipes used as black-body radiators have also been developed.

Stainless steel sodium heat pipes and vapor chambers are being used in electrically heated systems and heat-exchange systems of the hot flames of Stirling-type engines.

University of Delft (Delft): R (FE). Measurements are being conducted on the maximum capillary pressure of permeability of specimens made of single-layer (size 180) mesh and double-layer (size 180) mesh with 3 × 6 mm grooves and with grooves covered with single-layer mesh. The liquid coolant used was water with 0.05% dioctylsodiumsulfosuccinate added. This surface-active substance was used for improving the wettability of the stainless steel.

USSR

Institute of Heat and Mass Exchange Academy of Sciences of the Belorussian SSR (Minsk): R (FT, FE, AP), A (AT). Theoretical and experimental work was carried out on the dynamics of liquids and gases and on heat exchange in capillary-porous solids. The theory was based on solution of the Navier — Stokes equations, taking account of additional velocity terms for a singular surface and the discreteness of the thermodynamic properties on this surface.

Present plans call for the investigation of the problem of the transfer of momentum, energy, and matter on the basis of nonlinear thermodynamics of a capillary-porous solid.

Experimental research was conducted on evaporative cooling of porous solids in the presence of external and internal heat fluxes under vacuum conditions.

Theoretical and experimental studies were conducted on low-temperature coaxial heat pipes made of stainless steel and using ethyl alcohol as the coolant; the evaporator was placed inside the pipe, and the condenser was placed outside. Various types of wicks are under investigation. The evaporator and the condenser are connected by porous disks covered with a metal mesh.

Centrifugal coaxial heat pipes made of copper and using water as the coolant have been developed; the evaporator is placed on the outer surface of the heat pipe (a gas burner), and the condenser is placed inside the pipe (the inner cylindrical cavity of the coaxial heat pipe is cooled by a stream of water). Special attention is being given to achieving optimum conditions of evaporation and condensation at minimum thermal resistance.

Research is being conducted on heat pipes (with a wick and an artery) having variable thermal conductivity. A special type of heat pipe with a worm screw or helical tube placed in the vapor space has been developed. Freon-11, acetone, toluene, and carbon tetroxide have been used as working fluids. The use of a worm screw in the vapor space of the heat pipe results in turbulence of the vapor stream, making the heat exchange approximately three times as great. The use of a worm screw in the heat pipes with freon-11 as the coolant reduced the thermal resistance by 55%, and in a heat pipe using acetone as a coolant the thermal resistance was reduced by 80%.

High-Temperature Institute, Academy of Sciences of the USSR (Moscow): R (FE, FT). A theoretical analysis of the hydrodynamics of a heat pipe was carried out, using a gasdynamics approach based on the integral equations of the boundary layer in a cylindrical channel under conditions of isothermal gas flow.

Institute of Nuclear Physics (Obninsk): R (FT, FE, AP). The parameters of sodium heat pipes and vapor chambers were investigated experimentally.

A mathematical model taking account of the effect of friction on the sonic limit was developed. The theory is based on the one-dimensional equation of momentum for variable mass flow, on the equation of continuity, and on the equation of state for the vapor.

Moscow Power Institute: R (FT, FE, AP). Theoretical studies were carried out on hydrodynamic effects in heat pipes of small diameter at moderate temperatures for equal pressure-drop values in the vapor and the liquid. The dynamic effects produced by radial mass flow were considered. The theory used the Navier — Stokes equations for vapor flow and the following assumptions: a stream of incompressible vapor with constant physical properties; constant heat flux and constant wall temperature in the evaporator and condenser zones; the presence of a constant thickness of moist wick throughout the length of the heat pipe; an expression for the radial profile of vapor velocity along the axis in terms of a fourth-degree polynomial in a dimensionless radius coordinate; the presence of dry and saturated vapor; negligibility of the temperature jump at the liquid — vapor interface.

It was shown that the theory is in good agreement with experimental results. Theoretical and experimental investigations were carried out on low-temperature heat pipes with a mesh structure, taking account of the zone of deepening of the liquid in the evaporator, and low-temperature heat pipes (for example, using water as the working fluid) with variable thermal conductivity which consists of a cold reservoir and a wick.

Yugoslavia

Boris Kidric Institute (Belgrade): R (FT). Theoretical investigations of thermosiphons and heat pipes were carried out on the basis of a thermodynamic approach based on the second law.