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A NEW HYDRODYNAMIC LIQUID COOLING METHOD FOR EDGE-COOLED, FLAT CONDUCTOR MAGNET COILS AND FOR LIQUID-COOLED FERRITE RF RESONATOR DISCS

DISCLAIMER

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Summary

A method of efficiently cooling tape-wound, edge-cooled magnet coils, or ferrite discs results from the action of an inwardly-directed spiral free vortex flow pattern of the coolant. Many of the unfavorable hydraulic losses and heat-transfer limitations inherent in conventional internally-cooled magnet coils can be eliminated or minimized. The designer can independently control fluid velocities, turbulence, heat-transfer rate, fluid flow rate, bulk temperature rise, and coil space factor within wide limits by the use of hydrodynamic techniques. Hydraulic pumping energy can be minimized, conductor temperature rise can be reduced, and in many cases, the electrical current density in the conductors can be raised by the use of external vortex coolant flow.

The radial increase of fluid velocity toward the center matches the need for improved cooling of the inner portions of RF ferrite discs resulting from the increased heating at the inner rim. This reduces the hazard of thermal fracture in the brittle ferrite due to differential heating.

Current Practice and Difficulties in Cooling Coils

For some time it has been standard practice to cool the electrical conductors in a magnet coil by circulating a coolant (usually water) through an internal passage in the conductor. The magnet coil can thus be viewed as a heat exchanger. The heat generated by joule heating of the conductor as a result of electrical current flow is transferred to the coolant flowing through the conductor. Heat is generated in close proximity to the heat-transfer surface. The heat flow path from point of generation to the interface where heat is transferred to the coolant is extremely short, usually measured in fractions of an inch. The thermal conductivity of the electrical conductor is invariably very large; in the case of copper, about a thousand times that of the film thermal conductivity of the usual coolant, water.

The characteristics of the heat generation and transmission process is one of extremely low thermal impedance—very short heat transmission paths combined with high thermal conductivity of the metal conductor. In contrast, the coolant circuit is characterized by very high impedance from a fluid flow and thermal viewpoint. The coolant flow passage in the conductor is usually characterized by a small diameter and great length. In a single magnet coil, the length of the coolant passage is often hundreds of feet, but the diameter is only fractions of an inch. The length-to-diameter ratio of the coolant flow passage often exceeds 10 000 to 1.

From a thermal viewpoint, the heat-transfer process involves short paths but a relatively large thermal resistance due to the film heat transfer factor of the coolant. Thus, the thermal energy transfer to the coolant is one of moderately high thermal impedance.

Comparison of Magnet Coil Cooling with Heat Exchanger Design Problems

The design of a conventional heat exchanger involves a consideration of both the heat-transfer rates between the fluids and the mechanical pumping power expended to overcome fluid friction and move the fluids through the heat exchanger. For a heat exchanger operating with high-density fluids, the friction-power expenditure is generally small relative to the heat-transfer rate, with the result that the friction-power expenditure is seldom of controlling influence. That this is not the case with the usual internally-cooled conductor in a magnet coil is due to the small diameter but great length of the conventional coolant circuit. Recall that in coolant circuits the cost of fluid pumping energy is worth three to five times its equivalent in electrical power costs.

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For most flow passages that might be used for the heat-transfer surfaces of a conventional heat exchanger, the heat-transfer rate per unit of surface area can be increased by increasing fluid-flow velocity, and this rate varies as something less than the first power of the velocity. The friction-power expenditure is also increased with flow velocity, but in this case the power varies by as much as the cube of the velocity and never by less than the square of the velocity. It is this behavior that allows the designer of a conventional heat exchanger to match both heat-transfer rate and friction (pressure-drop) specifications, and it is also this behavior that dictates many of the characteristics of different classes of heat exchangers.

If in a certain heat-exchanger design, the friction-power expenditure is high, the designer can reduce flow velocities by increasing the number of flow passages in parallel. By so doing he will decrease the heat-transfer rate per unit of surface area, but according to the relations stated above, the reduction in heat-transfer rate will be considerably less than the friction-power reduction. The loss of heat-transfer rate is then made up by increasing the surface area (lengthening the tubes), which in turn also increases the friction-power expenditure, but only in the same proportion as the heat-transfer surface area is increased.

In contrast to the flexibility and freedom of choice afforded the designer of conventional heat exchangers, the magnet coil designer formerly had little freedom of choice in designing the internal fluid cooling circuit. The cross-sectional area of the coolant passage competes with the cross-sectional area of the conductor and reduces the space factor of the coil. The designer cannot use many circuits in parallel but is constrained to use a single flow passage equal in length to that of the electrical conductor. A long flow passage of small diameter usually requires high pressure drop, and since the heat capacity of the coolant is limited, the bulk temperature rise of the coolant from beginning to end of the circuit is large.

Advantages of Hydrodynamic Flow Systems for Cooling Purposes

The designer of magnet coils can now avoid many of these constraints. He can now rely upon hydrodynamic forces rather than hydrostatic forces for directing the flow of fluid coolants, and he can use these hydrodynamic forces to control the fluid velocities and flow rates in order to maximize heat-transfer rate with minimum space for coolant passages.

When hydrodynamic forces instead of the usual hydrostatic forces are used to direct the flow of fluid within the walls of a cooling passage, pressure must first be converted into velocity, and the resulting kinetic energy and momentum of the moving fluid directs the flow in the desired manner.

Theory of Simple Fluid Motions

In the process of building up complete flow pictures by superimposing known flow pictures of simple fluid motions, we have investigated two such simple fluid motions. They are the "sink" and the "free vortex."

Hydraulic Sink

In the sink, the fluid is assumed to be converging to a common center, the flow proceeding along straight radial lines. This flow can, with the exception of its innermost portion, be achieved between two parallel walls with a central side outlet, as shown in Fig. 1. Because of its complete axial symmetry, there is no reason to assume anything but uniform velocity distribution along concentric circles. The cross sections of this flow are concentric cylinders of constant length (axial width) and are therefore proportional to their respective radii; it therefore follows from the condition of continuity that

$$V_r \cdot r = \text{constant} ,$$

or that the velocity of a sink is inversely proportional to the distance r from the center. It is obvious that the higher velocities near the center must be accompanied by a lower static pressure in this region, according to Bernoulli's equation.

Free Vortex

The flow of the free vortex is also of great practical importance. The flow is again one of constant energy, proceeding along concentric circles as shown in Fig. 2.

Although the form of the stream lines is given, their spacing is not; and therefore the velocity distribution cannot be derived simply from the condition of continuity, as in the case of the sink, but must be obtained by dynamic considerations. This leads to the well-known law of constant angular momentum

$$V_u \cdot r = \text{constant} ,$$

or, stated verbally, the velocity of a vortex of constant energy, or free vortex, is inversely proportional to the distance r from the center of rotation. Since both V_r of the sink and V_u of the free vortex are total velocities, it is seen that the magnitude of the velocity of flow varies in the same manner for these two forms of fluid motion. The difference between the two flow pictures therefore lies solely in the direction of the flow.

The sink and the free vortex are the only elementary flow pictures that will be considered here. These two forms of fluid motion are sufficient for us to construct, by the principle of superposition, the most important flow picture needed to visualize a new method of effectively cooling flat rectangular conductor magnet coils with edge cooling.

Spiral Free Vortex

The flow picture shown in Fig. 3 is obtained by the superposition of a sink and a free vortex. This flow picture is called a "spiral free vortex," with inwardly-directed flow in accordance with the form of the resulting stream lines.

The total velocity V of this flow can be obtained by the vectorial addition of the radial and peripheral velocities V_r and V_u as shown. Since both velocity components vary according to the same law, it follows that their ratio must be constant, so that the flow angle β is everywhere the same. The resulting stream lines are therefore lines of constant inclination and are thereby characterized as logarithmic spirals.

Configuration Recommended for Coils, Nozzles, and Coil Tank

In order to achieve the advantages of a spiral free vortex type of flow, we must arrange the tape-wound coils and coil tanks in the following configuration:

The flat conductor magnet coil units are mounted with a space of at least one-half inch between adjacent coils and with similar spacing between the end coils and the coil tank wall. For ac magnets, the coil tank is provided with a pressure-tight nonconducting joint to prevent the effect of a shorted turn.

A coolant supply manifold around the periphery of the coils is provided with a series of orifices or nozzles located on the median plane between the coils and directed tangentially or at a low angle to the tangent into the space between coils and the space between end coils and tank wall.

The fluid-pressure drop across the nozzles or orifices produces a series of submerged jets on the median plane between adjacent magnet coils; these jets produce very high turbulence in the body of coolant as their momentum is absorbed. This high degree of fluid turbulence in the intercoil and end spaces results in extremely effective cooling.

Approximately one-half of the kinetic energy contained in the fluid jets is converted into angular momentum of the rotating fluid mass between and around the magnet coils. As the fluid flows inward with a considerable rotational component, the angular momentum is conserved, with a resulting increase in tangential velocity as the radius becomes smaller according to the principles of the free vortex. The radial component of the fluid velocity also increases as the flow converges with diminishing radius.

The increased velocity of flow generates increased fluid turbulence, which in turn results in very effective cooling of the inner-turns of the magnet coil; this more than compensates for the reduction of the fluid turbulence generated near the outer radius as the multiple jets of fluid are absorbed into the fluid mass.

Application to Ferrite Disc Cooling

This method of utilizing the properties of a vigorous, jet-induced spiral-free vortex flow pattern in an annular space that is thin axially is especially effective for the cooling of ferrite resonator discs, because the RF power density varies inversely with the square of the radius. With the ferrite disc resonators proposed for the Omnitron accelerator, the RF power density producing heating of the ferrite becomes 7 times as great at the inner rim of the disc. The fluid velocities resulting from a jet-induced spiral-free vortex flow pattern between adjacent discs would produce just the type of cooling that the ferrite disc heating pattern requires. This reduces the hazard of thermal fracture of the brittle ferrite due to differential heating.

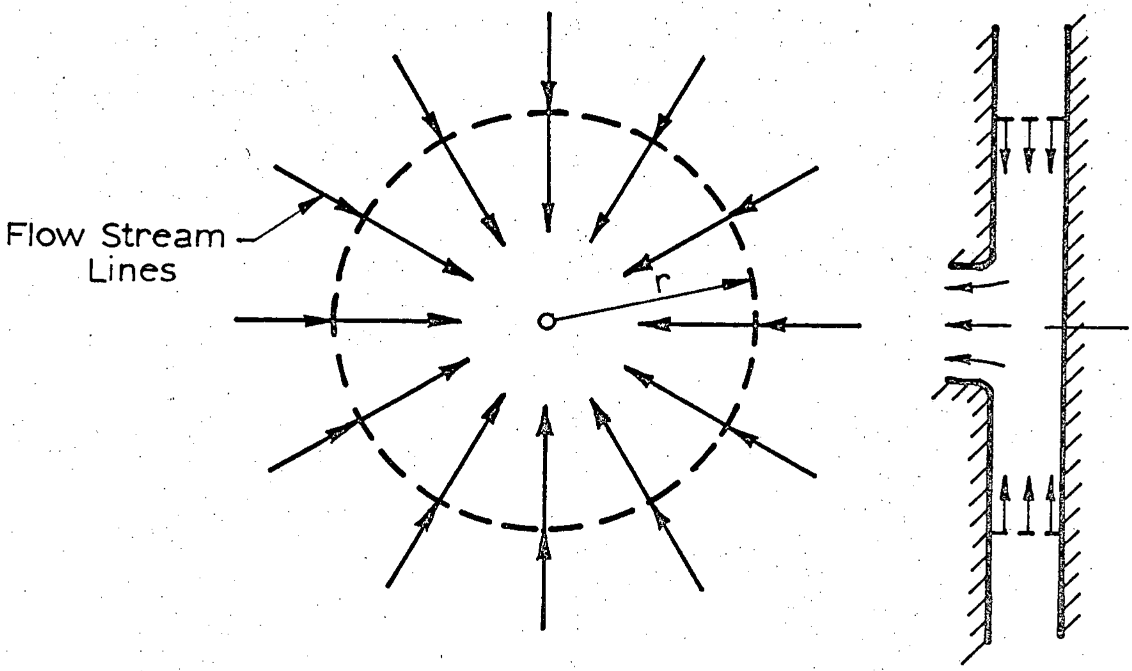

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Fig. 1. Sink

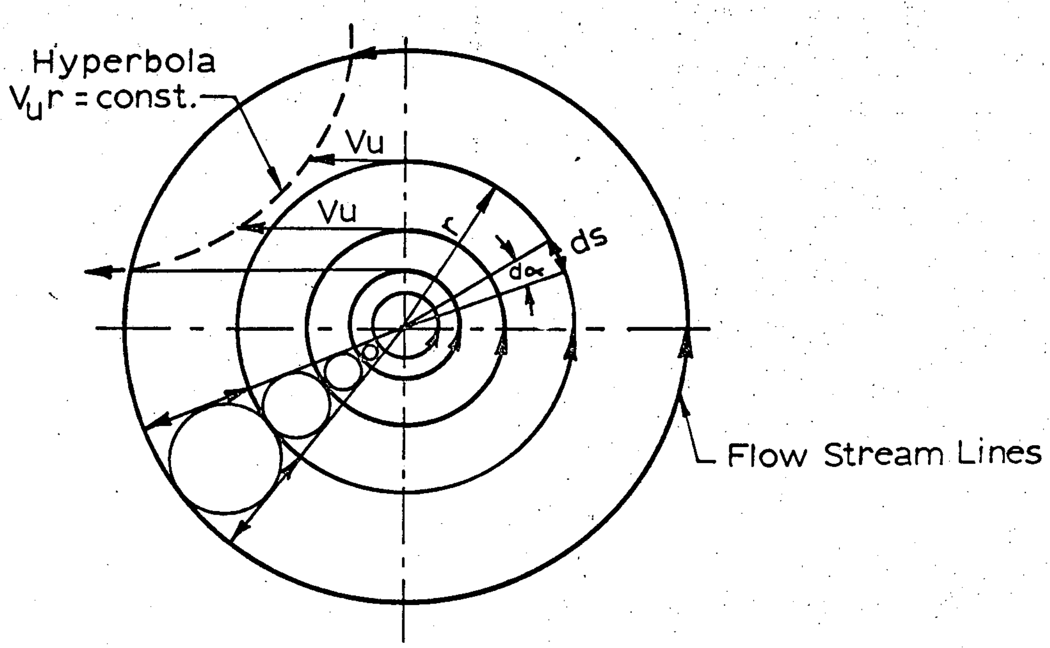

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Fig. 2. Free vortex

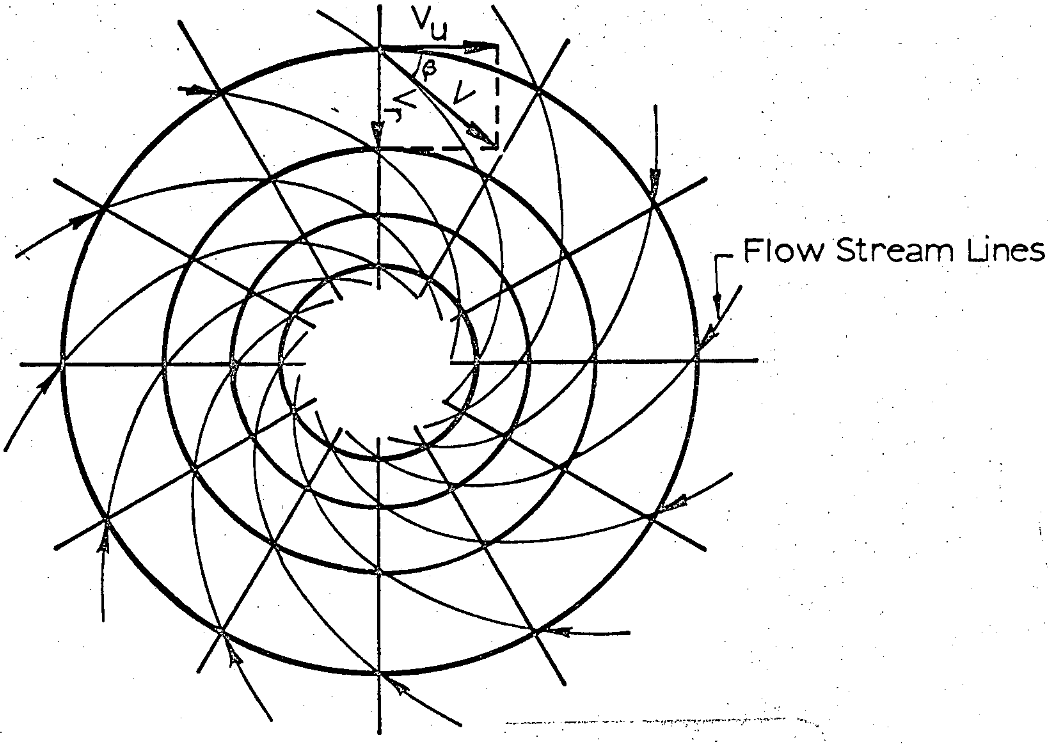

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Fig. 3. Spiral vortex