Heat transfer and recovery performance enhancement of metal and superconducting tapes under high current pulses for improving fault current limiting behavior of HTS transformers

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Abstract:

High temperature superconducting (HTS) transformers windings operate subcooled at atmospheric pressure to temperatures as low as 65 K, with minimal power dissipation from AC loss in normal operation. During short circuits, HTS transformers are subjected to transient heating by currents as much as 10x rated current for durations of up to 2 s. After isolating the fault, HTS transformers are required to cool back down to their base temperature while carrying the operating current. HTS transformer conductors are insulated, typically with wrapped self-adhesive polyimide tape, and windings consist of close packed conductors wound on composite formers.

In this paper, the heat transfer, transient thermal response, and recovery performance of brass-laminated coated conductor HTS wire as well as metallic conductors in liquid nitrogen (LN2) were measured at a range of temperatures from 77 K to 64 K and pressures from atmospheric to 0.14 bar in heating and cooling situations. Measurements were made on bare tapes, and on tapes wrapped with polyimide insulation tape and with aramid paper as well as polymer coated tapes with a range of coating thickness. Heat transfer from tapes mounted with one face in contact with a glass-epoxy composite cylindrical former was measured for comparison with free-standing tapes. Using conductors with solid polymer coatings of optimized thickness immersed in subcooled LN2 results in the highest heat transfer and fast recovery following heating to 300 K by a high current pulse. Compared to a bare tape in LN2 at ambient pressure at 77 K, the heat transfer in a coated tape in 65 K subcooled LN2 can be very significantly enhanced, by up to a factor of 15x, and recovery can be 7x faster.

Keywords: Fault performance, Heat Transfer, High Temperature Superconductors, Liquid Nitrogen, Recovery Time, Solid Coating, Short circuit current, Subcooling, Superconducting transformer, Superconducting Fault Current limiter.

1. Introduction

Power transformers are required to withstand the fault current for up to 2 s stipulated in IEC test standards¹ and required by network operators to continue to carry current during a fault to allow time for protection systems to isolate only the faulty section of the power network. A further requirement is the need to continue to operate at rated current after the fault is isolated. For large conventional power transformers, with relatively massive copper or aluminium conductors operating at rated current densities of around 3 to 5 A/mm², and fault currents up to 10x higher, these requirements are routinely met. For high temperature superconducting (HTS) conductors of superconducting transformers, with much higher current densities and lower thermal mass, these requirements are extremely challenging. In contrast, resistive

superconducting fault current limiters² (SFCLs) are typically isolated from the fault current within 5 to 10 cycles, and recover while disconnected, so heat transfer is not a primary concern, and thus, the design assumes adiabatic heating during the fault, i.e. ignoring any heat transfer. Therefore, heat transfer in liquid nitrogen (LN2) is critically important in the design of HTS transformers. Heat transfer by natural convection and pool boiling affect transformer performance both in normal operation, where natural convection limits the temperature rise produced by AC loss³ in the HTS windings, but also during a fault current event and subsequent recovery, where maximizing the boiling heat transfer is a crucial design objective if HTS transformers are to perform to the standards required by power networks.

Most of the literature work on heat transfer in LN2 are in equilibrium conditions. Heat transfer shows a progressive transition with increasing heat flux from natural convection to nucleate boiling to film boiling⁴. Transient heat transfer, with rapidly increasing heat flux, has been shown to produce a transition to film boiling at lower heat flux than in equilibrium conditions⁵. Surface roughness has a major influence on nucleate boiling, with rough surfaces exhibiting higher heat flux at lower surface temperature than smooth surfaces⁶. Surface orientation also has an effect⁷.

Insulating coatings can significantly improve boiling transfer^{8,9}. The effect has been known for over 50 years¹⁰, and was patented in 1969¹¹. A coating with appropriate thermal resistance keeps the surface cold enough to avoid film boiling and remain in the nucleate boiling regime with its higher heat transfer coefficient. We refer to this phenomenon as extended nucleate boiling (ENB) in this paper.

Earlier measurements specifically targeting heat transfer in HTS transformer applications include measurements of cool-down under load in single layer solenoid windings¹² and of heat transfer from Roebel cable solenoid windings¹³ at low heat flux exploring the transition from natural convection to nucleate boiling in saturated vapor pressure (SVP) and subcooled LN2.

Transformer windings operate with AC current and voltage, and often with high electric fields in parts of the windings. The latter has been shown to enhance boiling heat transfer in LN2¹⁴. In practice, the bulk of each transformer winding experiences quite low electric fields, around 50 V/mm, set by the turn to turn voltage; only the extremities of the windings are subjected to fields of kV per mm.

The distinctive characteristics of HTS transformer windings from the perspective of heat transfer are:

1. Transient heating at high fault current levels sustained for up to 2 s, raising the conductor temperature possibly as high as 450 K^{15,16,17}
2. Recovery (cool-down) after the fault to the superconducting state, ideally while carrying rated current
3. Operation in subcooled LN2– to lower the operating temperature for improved critical current, and to avoid boiling and the consequent risk of electrical breakdown in normal operation
4. Electrically insulated wire – in conventional transformer manufacture the insulation is typically wrapped kraft paper
5. Conductors mounted under tension in contact with insulating formers so they are able to resist the mechanical stresses of the fault current.

Accordingly, in this work we report measurements of heat transfer in LN2 from ReBCO HTS wire heated by high current pulses to temperatures as high as 300 K. Conductor temperature and heat transfer were measured during transient heating as well as during cooling. Measurements were done in LN2 in SVP conditions at ambient pressure, with temperature of 77.4 K, as well as subcooled, usually at 65 K at ambient pressure. Tapes with a range of surface treatments were investigated: bare, and with Kapton polyimide self-adhesive tape, Nomex aramid paper wrap, and with UV-cured polyurethane coatings. Finally, the heat transfer from free-standing tapes was compared with the same tapes mounted under tension in a trench milled in a composite former. Our aim was to provide the heat transfer and recovery information required to design the windings of current-limiting fault tolerant HTS transformers¹⁸.

2. Experimental setup

2.1. High current pulse and heat transfer measurement technique

In this paper, the input power and resistance are calculated from measurements of the current and voltage across a sample¹⁹. The temperature is calculated using a calibration of the sample resistance as a function of temperature. The samples in the present study were tapes with typical width of 4 to 5 mm, because this is a standard form of HTS tape in large scale applications, specifically in HTS transformers. Tape samples were either brass-laminated HTS tapes (AMSC type 8700) or metallic ones such as copper and brass. Copper and brass were used as samples in this study because most commercial superconducting tapes have copper or brass stabilizer, and, current passes through the stabilizer during a short circuit fault rather than the superconductor itself. Note that the temperature determined from the resistance measurement is an average of the sample temperature. Temperature gradients through the depth of the samples will be small; for a very large heat flux of 2×10^5 W/m² normal to the tape surface, the temperature difference between the centre and surface of a 0.3 mm thick brass tape (thermal conductivity at 100 K $\sim$ 50 W/m K) will be only 0.3 K. However, large transient temperature variations along the length of a sample are possible during the transitions between heat transfer regimes, which have been observed in HTS tape samples using high-speed photography²⁰. Without the benefit of such observations, we maintain that the reproducibility of the results and the attainment of a stable heat flux suggest that the sample has uniform temperature and heat transfer regime along its length.

Much of the experimental work on heat transfer in literature is concerned with equilibrium conditions, with $\frac{dT}{dt} = 0$, so that the input power is equal to the heat transferred. For the transient heat transfer of interest during short circuits in HTS transformers, it is necessary to take the heat capacity of the sample into account. The energy balance is expressed by:

$$P_{in} = VC_{pv} \frac{dT}{dt} + P_{out} \quad (1)$$

P_{in} is the electrical power supplied to the sample, with volume V . The heat transfer from the sample to the liquid, P_{out} , is obtained by differentiating the $T(t)$ curve and using volumetric specific heat data $C_{pv}(T)$ from the literature^{21,22} to correct for the heat capacity of the sample. The resistivity of copper²³ and brass²⁴ is quite accurately linear in temperature in the range between 65 K and 300 K, so that we calculate the temperature from the measured sample resistance by linear interpolation between measurements made at low current density at ambient temperature and at the base temperature of the cryogen. The resistance of a sample of the superconducting tape as a function of temperature was measured from room temperature to the superconducting transition to provide a temperature calibration curve for the heat transfer measurements on these samples.

The measurement setup uses a DC power supply to apply either constant current or constant voltage pulses to heat the sample. Two different power supplies were used depending on the required current level, one with 580 A, 8 V output and the other 1000 A, 3 V. The current was measured using an HP3458A DVM to measure the voltage across a 0.1 m Ω shunt resistance. A second HP3458A DVM measured the sample volts. The measurements of the two DVMs were synchronised, with measurements taken every 25 ms, and each point integrated over one power line cycle, 20 ms.

The current pulse applied to the samples consisted generally of three steps, with current levels I_0 , I_{short} , and $I_{recovery}$. The initial current I_0 was set at a level, typically 10 A or less, sufficient for accurate resistance measurement but with low power dissipation so that the sample temperature would deviate very little from the cryogen liquid temperature. The high current pulse I_{short} then heats the sample. The recovery current was set to a range of levels: a low level, the same as I_0 , to record free cooling, or higher levels with appreciable dissipation to reproduce the cooling of HTS transformer windings after a short circuit. The corresponding duration of each of the current steps are t_0 , t_{short} , and $t_{recovery}$. The duration of the

heating pulse, t_{short} , was typically 2 or 4 seconds when investigating heat transfer in equilibrium conditions; but was much shorter, around 0.2 s, when the intention was to reproduce the rapid heating of HTS transformer windings during an external short circuit. Some experiments were performed with longer heating pulses of 6 or 8 seconds to confirm the equilibrium condition had been attained.

2.2. Cryostat

Figure 1 shows a cryostat insert for a 10-litre stainless steel thermos flask which was designed and constructed for measurements in subcooled conditions from atmospheric pressure down to 0.1 bar. The usual target conditions were those for an HTS transformer, 65 K at atmospheric pressure. The cryostat was divided into two levels by a thermal barrier of polystyrene foam; the upper level contained surface LN2 at 77 K, and below it the subcooled experimental compartment. The barrier is loose-fitting so that pressure in the two levels is equalised. The subcooled compartment is cooled by evaporative cooling using a rotary pump which draws LN2 from the upper compartment through a throttling valve into a heat exchanger made from copper tube formed into a horseshoe-shaped loop. The pumping pressure is controlled by a manometer. Three PT-100 temperature sensors in the subcooled volume are used to monitor the temperature of the throttling valve and to confirm temperature uniformity at the sample location. In addition, several PT-100 sensors were used in top compartment to monitor the LN2 level so the cryostat could be periodically refilled from an external dewar.

Figure 1. Cryostat Layout showing subcooled LN2 space and copper heat exchange coil below the bottom barrier of polystyrene foam.

Figure 2. The sample on the former configuration in the subcooled LN2 space of the cryostat.

Samples were measured in two configurations; isolated (free standing) and mounted in tension in a groove, wrapped around a G-10 epoxy-glass composite former, which was shown in Figure 2. The outside diameter of the former is 140 mm. The free-standing samples were also mounted bent almost in a complete circle of the same diameter, positioned about 15 mm above the bottom of the cryostat. The standard sample length was 400 mm, with voltage taps spaced 120 mm apart symmetrically placed around the sample centre. The width of the sample tape was oriented vertically, the same as HTS transformer windings with vertical axes.

2.3. Sample coating process

Heat transfer can be increased by coating a metal surface. We applied coatings of UV-cured polyurethane resin of various thicknesses on HTS tape as well as 4 x 0.3 mm copper tape using a Mayer rod coating set-up. Coatings with average thicknesses of 44.2, 56.6, 101.2, and 120.7 μm were applied using Mayer rods wound with a range of wire diameters. Note that the coatings were not subjected to electrical insulation testing. A practical coating would need to not only enhance the boiling heat transfer of the conductor but also have the required electrical insulation performance.

3. Experimental results and discussions

3.1. Heating at 77 K SVP and subcooled LN2

The first set of heat transfer experiments involved heating free-standing samples immersed in LN2 at 77 K SVP. These are essentially transient heating experiments, but within the 2 sec duration of the heating pulse, at lower power levels equilibrium conditions are approached: temperature tends to constant value, implying the input power is balanced by heat transfer from the tape to the LN2.

Figure 3 shows the conductor temperature versus time for constant current pulses of duration 2 sec applied to a 0.3 mm thick bare copper tape immersed in LN2 at 77 K.

Figure 3. Conductor temperature versus time for constant current pulses of duration 2 sec for 0.3 mm thick copper tape immersed in LN2 at 77 K SVP. The legend gives power density in W/cm^2 . Symbols are to identify the curves; measurements were made at 25 ms intervals.

Curves are labelled with the surface power density, with the value taken to be the power density limit approached as the temperature approached its equilibrium value. Since the majority of our experiments were made on free-standing samples the surface area of both sides of the sample is used to calculate power density and heat flux unless otherwise stated. The small peaks at 2 s are artefacts caused by the rapid change in voltage and current at the end of the heating pulse.

Three different heat transfer regimes: natural convection, nucleate boiling, and film boiling, can be distinguished in Figure 3, as reported by other researchers who observed similar successions of transient temperature response curves^{5,25}, as follow:

1. *Convection*: The conductor temperature increases monotonically to a plateau. The difference between the average temperature of the conductor and the bulk liquid nitrogen, ΔT , is less than 9 K, and current density less than 130 A/mm². The power density is up to 0.7 W/cm². At 0.93 W/cm², the temperature drop occurs in distinct steps, possibly reflecting the passage of a nucleation front as observed in high-speed camera observations²⁰. The sample then settles at a constant temperature. This is the second heat transfer regime, nucleate boiling.
2. *Nucleate Boiling*: In these transient heating experiments, this state is reached after passing through a temperature peak occurring as soon as 0.3 s after onset of heating, with the average sample temperature reaching as high as 92 K. The sample then experiences rapid cooling, which implies the sudden evaporation of the layer of liquid nitrogen closest to the surface. The maximum measured heat flux in the nucleate boiling regime is about 2.4 W/cm².
3. *Film Boiling*: In equilibrium heat transfer conditions the transition from nucleate boiling to film boiling occurs when the heat flux exceeds the critical heating flux (CHF). The heat transfer coefficient $q/\Delta T$ in film boiling is comparatively low because a sheath of vapour insulates the hot surface of the conductor from contact with the liquid nitrogen. The onset of film boiling is seen in Figure 3 at a current density of 261 A/mm², corresponding to a threshold average power density of around 4.7 W/cm². With the transition to film boiling power, thermal runaway occurs and the average conductor temperature rises to around 200 K by the end of the 2 s heating pulse.

A distinction should be made between the transition from nucleate boiling to film boiling observed in equilibrium conditions and in these transient rapid heating experiments. In equilibrium nucleate boiling conditions, a slight increase in thermal flux above the critical heating flux of around 20 W/cm² produces a boiling crisis²⁶ with the surface drying out as LN2 can no longer reach the nucleation sites due to the volume of escaping vapour. In contrast, the transition we observe involves the surface cooling from a transient temperature maximum with $\Delta T > 10$ K to re-establish stable nucleate boiling, with $\Delta T \sim 2$ K. It is probable that the rapid onset of boiling is nucleated at the same surface nucleation sites activated at critical heating flux, rather than by homogeneous nucleation in the superheated layer of LN2 at the surface, since there is no obvious change in the $T(t)$ curves with increasing power density. At high enough power density, the heat removed from the surface by the onset of boiling is insufficient to lower its temperature into the range for stable nucleate boiling, the nucleation sites are starved of liquid, a sheath of gas surrounds the tape, and thermal runaway ensues.

A further set of heat transfer experiments was conducted in subcooled LN2 at atmospheric pressure, the preferred operating conditions for HTS transformers. Transient heating experiments were performed on copper samples with longer pulses up to 4 s heat pulse duration. Heat transfer experiments were done at two different subcooled LN2 temperatures; 70 K and 65 K. Figure 4 shows the conductor temperature versus time for constant current pulses of duration 4 sec applied to a 0.3 mm thick bare copper tape immersed in subcooled LN2. We see a succession of temperature traces, similar to those at 77 K SVP in Figure 3, revealing the transition from natural convection to nucleate boiling followed by the onset of thermal runaway. At 70 K, convective heat transfer is stable up to a conductor temperature of 85 K, $\Delta T = 15$ K, at power density up to about 1.0 W/cm². Nucleate boiling is initiated at a power density range of 1.5 W/cm² with thermal runaway

occurring at 6.5 W/cm². At 65 K, convective heat transfer is stable to the same maximum conductor temperature of 85 K, $\Delta T=20$ K, to a significantly higher power density, up to about 2.1 W/cm². Nucleate boiling occurs in the power density range of 5 W/cm² to 12.6 W/cm² with thermal runaway beyond 13 W/cm².

From Figure 4, it can be concluded that the lower LN2 temperature in subcooled conditions increases the maximum heat transfer before thermal runaway, increases the maximum permissible current density before runaway, and extends the allowable temperature difference between conductor and LN2 in each heat transfer regime, which are all quite important for fault tolerant superconducting transformer applications¹⁸.

Figure 4. Conductor temperature versus time for constant current pulses of duration 4 sec for 0.3 mm thick copper tape immersed in subcooled LN2 at atmospheric pressure. The legend gives power density in W/cm². Symbols are to identify the curves; measurements were made at 25 ms intervals.

Figure 5. SNC and SNB curves versus conductor temperature for 0.3 mm thick bare copper tape immersed in LN2 at SVP and subcooled to 70 and 65 K, all at atmospheric pressure

From the equilibrium temperatures and power densities in Figures 3 and 4, we can plot the heat transfer curves for stable natural convection (SNC) and stable nucleate boiling (SNB) shown in Figure 5. It can be seen that subcooling from 77 to 65 K increases the maximum convective heat transfer by more than a factor of 3x, from around 0.65 to 2.1 W/cm². The SNC curves are close to linear, but are well fit by a power law with exponent slightly greater than unity, as follows:

$$a(T - T_0)^{1+\delta} \quad (2)$$

The fit data for the SNC curves are tabulated in Table 1.

Table 1. The fit parameters for the SNC curves derived from Figure 5

Fit Parameters for	T_0 (K)	a (W/ cm ² .K)	δ	$q_{\max}$ (W/cm ²)
SVP 77K	77.3	0.057	0.074	0.65
Subcooled 70K	70.5	0.051	0.17	1.2
Subcooled 65K	65.8	0.059	0.15	2.1

The obvious feature of the SNC curves is that they are displaced along the temperature axis i.e. they scale with $\Delta T = T - T_0$, with the base temperature T_0 changing with the different LN2 temperatures. They terminate at a common maximum temperature around 87 K corresponding to the maximal superheating for the sample surface in these transient heating conditions. In contrast the heat transfer curves for stable nucleate boiling at different LN2 temperatures shown in Figure 5 seem to be segments of a single curve, with heat flux depending only on the conductor temperature. This perhaps reflects the fact that the latent heat of vaporisation of the liquid, at 199 kJ.kg⁻¹ [27], dominates the boiling heat transfer compared to the specific heat required to raise the liquid temperature to that of the conductor, 2 kJ.kg⁻¹.K⁻¹. The effect of lowering the temperature of the LN2 below 77 K is mostly to alter the range of heat flux in which stable nucleate boiling can be maintained. In particular, the maximum heat flux attainable before thermal runaway intervenes is increased. This can be

understood as follows. As bubbles form at nucleation sites and grow and detach from the surface, they come into contact with subcooled liquid and condensation of the vapour will cause the bubbles to shrink and eventually collapse. This reduction in bubble volume allows better circulation of liquid to the nucleation sites and so higher heat flux can be managed before surface drying brings about the transition to film boiling. The maximum temperature and minimum and maximum heat fluxes for the segments of the SNB heat transfer curve accessible with different degrees of subcooling are listed in Table 2.

Table 2. Parameters for the SNB curves in Figure 5

Experimental conditions	$T_{\max}$ (K)	$q_{\min}$ (W/cm ²)	$q_{\max}$ (W/cm ²)
SVP 77K	82.8	1.8	3.5
Subcooled 70K	83.8	3	7
Subcooled 65K	85.9	5	13

Note that all the results were measured on a single piece of tape as received. The reason there is a gap between the highest heat flux point on each SNC curve and the lowest point on the corresponding SNB curve is that, in this range, boiling began within the 2 s pulse duration but there was insufficient time to establish SNB.

3.2. Cooling and recovery phase

Heat transfer measurements during transient cooling from around 300 K are considered in this section. This type of heat transfer study is very important for predicting the recovery of the windings of an HTS transformer after a short circuit fault. We compare heat transfer in 3 conditions: subcooled 67 K and SVP 77 K, both at atmospheric pressure, and SVP 64 K, at a nominal pressure of 0.145 bar.

To measure the heat flux in cooling from around 300 K, we aim to mimic conditions during a short circuit fault of superconducting power transformers, heating the conductor in near-adiabatic conditions to minimise heat transfer during the heating pulse. Therefore, we heat the sample with a high current pulse of duration less than 0.35 s. This is difficult to achieve repeatedly with copper tapes in constant current mode measurements. The rapid increase in the resistivity of pure copper with temperature ($\rho(300\text{ K})/\rho(77\text{ K}) > 7$) means that $\frac{dT}{dt} \propto \rho J^2$ can be extremely high, and any slight inhomogeneity in heat transfer produces positive feedback so the tape easily becomes subject to non-uniform heating, evidenced by locally discoloured hotspots observed after some of measurements and by frequent burn-out of samples. Consequently, we used constant voltage excitation for the heating pulse as well as using brass samples, for which $\rho(300\text{ K})/\rho(77\text{ K}) \sim 1.5$, for some of the cool-down experiments.

Figure 6 shows conductor temperature versus time for constant voltage pulses of different duration in a 0.3 mm thick copper tape immersed in LN2 at 77K SVP including the cool-down, and recovery measured with much lower current density ($\sim 7\text{ A.mm}^{-2}$) and negligible input power level. Short pulses of different duration were applied to the sample. Table 3 lists maximum temperature, corresponding pulse energy, and cool-down time for this test.

Figure 7 shows the maximum temperature as a function of the pulse energy and the maximum temperature calculated from the specific heat assuming adiabatic heating. The results show that heating is near-adiabatic for heating at these high rates, at peak power from 25 to 75 W/cm² of surface area. Fully 93% of the power is used to heat the tape, and only 7% transferred to the LN2 during the heating pulse.

Figure 6. Conductor temperature versus time for constant voltage pulses of different duration in 0.3 mm thick copper tape immersed in LN2 at 77K SVP showing cool-down from different maximum temperatures. The legend gives pulse energy in J/cm^2

Table 3. The maximum temperature, heating pulse energy, and cool-down time for the rapid heating experiments of Figure 6

Maximum Temperature (K)	137	185	228	260	288	300
Corresponding Pulse Energy (J/cm^2)	4.7	9.3	13.8	17.4	20.4	20.8
Cool-Down Time (s)	1.9	3.4	4.6	5.1	5.6	5.7

Figure 7. Maximum temperature reached after high current pulses of duration around 0.2 s as a function of energy delivered by the pulse. The maximum temperature predicted using heat capacity data from the literature is shown by the solid line.

Figure 8. Cool-down time for free-standing 5 x 0.3 mm copper tape in LN2 at 77 K SVP as a function of initial temperature

Figure 9. Heat transfer versus conductor temperature during cool-down starting from various maximum temperatures for a 0.3 mm thick copper tape immersed in LN2 at 77K SVP.

Figure 8 shows the cool-down time as a function of maximum temperature. The cool-down time for this 5 x 0.3 mm copper tape appears to be approaching a limit at around 6 s as the maximum temperature reaches 300 K.

Figure 9 shows the heat transfer versus conductor temperature for cooling from different maximum temperatures calculated from the cooling portions of the $T(t)$ curves of Figure 6. In each case, heat transfer declines at first almost linearly from the maximum temperature in the film boiling regime. After reaching the Leidenfrost minimum²⁸ at 110 – 115 K, the heat transfer increases as nucleate boiling is initiated. Apart from the initial artefact peak, the film boiling curves are remarkably reproducible, and independent of T_{max} . The nucleate boiling peaks are much more variable, reflecting perhaps the stochastic nature of nucleation, since the peak is traversed in little more than 0.2 s in the steep final section of the cooling curves in Figure 6. The peak values of around 3 W/cm² are consistent with the maximum heat transfer from stable nucleate boiling in LN2 at 77 K SVP shown in Figure 5.

HTS tape with brass stabilizer is a promising option for manufacturing HTS transformer windings¹⁸, as well as SFCLs. For this reason, the effect of subcooling on heat transfer in the cooling phase was investigated using a 0.9 mm thick 5.6 mm wide brass sample. In addition, the thicker brass samples, with greater heat capacity, cool more slowly, reducing the measurement uncertainty. From the results shown in Figure 10 it is clear that, at 1 bar, the heat transfer in subcooled LN2 is higher than in the SVP condition. The peak nucleate boiling heat transfer in subcooled LN2 at 67 K is about 2.5x that at 77 K SVP. In the film boiling regime also the heat transfer in subcooled LN2 is about 50% higher than 77 K SVP. The nucleate boiling peak in the subcooled LN2 occurs at around 105 K, and the Leidenfrost minimum, at which the transition from film boiling to nucleate boiling begins, is at 150 – 160 K. Another interesting observation is that the heat transfer at 67 K subcooled is even higher than 64 K SVP. The Leidenfrost minimum and nucleate boiling peak for the heat transfer curves in 77 K and 64 K SVP LN2 and are displaced in temperature by approximately the 13 K difference in saturation temperature at 1 atm and 0.145 bar. The film boiling heat transfer at 0.145 bar (64 K SVP) is reduced compared to 1 bar (77 K SVP) presumably because a smaller rate of liquid evaporation is required to maintain a given average thickness of the insulating vapour film at the lower pressure. These results are very significant for the design of HTS transformers. Operation in subcooled LN2 is beneficial, not only to improve the critical current and AC loss of the wire and to avoid the bubble-induced reduction in breakdown voltage of the LN2 dielectric, but also to improve heat transfer for better performance during recovery after a short circuit¹⁸ fault.

Figure 10. Heat transfer of bare brass tape in LN2 subcooled to 67 K at 1 bar, and at SVP at 1 bar (77 K), and 0.145 bar (64 K)

3.3. Effect of conductor coatings on heat transfer performance during a short circuit fault

A major aim for these heat transfer studies was to provide information to guide the design and materials selection for a 45 kVA fault tolerant transformer demonstration¹⁸. The wire selected for the demonstrator (based on the results of this paper) was AMSC type 8700 type Amperium wire, a brass-laminated wire, 0.44 mm thick and 4.4 mm wide with tinned brass external surfaces. To ensure that the heat transfer characteristics of coatings applied to the HTS wire were representative of those obtained using a long-length coating system, type 8700 wire was adopted as sample material for these heat transfer measurements. A measurement of wire resistance as a function of temperature from the conductor's critical temperature at around 90 K to 300 K was done to provide the temperature calibration curve needed for heat transfer experiments. The critical current of the HTS tape was measured to be 109 A at 77 K, 272 A at 65 K.

Short samples (0.55 m length) of the Type 8700 wire were coated using a Mayer rod coating system to apply UV-cured polyurethane (PU) resin coatings with 4 different nominal coating thicknesses: 45, 55, 100, and 120 μm . The measured average thicknesses of the coatings were 44.2, 56.6, 101.2, and 120.7 μm with standard deviation between 1 and 2 μm .

Kapton polyimide adhesive tape has been used as wrapped turn-to-turn insulation in HTS transformers²⁹. For comparison with the PU coatings of a uniform thickness of Kapton adhesive tape, the bare HTS wire was sandwiched between two strips of 10 mm-wide tape with the edges of the adhesive tape extending beyond the edges of the wire carefully sealed together. Figure 11(a), 11(b) show conductor temperature versus time and heat transfer versus conductor temperature plots respectively for AMSC 8700 type HTS tapes with different coating thicknesses immersed in subcooled LN2 at 65 K, 1 bar pressure. The HTS tapes were heated to temperatures around 300 K with high current pulses of duration 0.27 to 0.38 s. Measurements during the cool-down phase were made with a current of 10 A flowing, corresponding to input power of around 450 W/m² at 300 K, dropping to half this at 90 K. This is negligible as it is only about 1% of the lowest heat transfer flux measured. Note that the apparent rapid cooling at the end of each trace apart from that for the bare tape reflects the transition to the superconducting state, which makes accurate temperature measurements impossible below about 90 K. The increase in slope below 150 K for the bare conductor marks the transition to nucleate boiling for this sample.

It is apparent from Figure 11(a) that the PU coated conductors cool more rapidly than the bare and the Kapton coated conductors. The conductors with the thinner PU coating, 45 and 55 μm , initially cool more slowly than the conductors with thicker coatings, but the rate of cooling then increases rapidly, so that they have the shortest cool-down times, well under 1 s. This variation in heat transfer with temperature is reflected in the heat transfer curves in Figure 11(b) which show that the heat transfer with the 40 and 55 μm coatings peaks at around 170 and 200 K respectively, whereas with the thicker PU coatings, the heat transfer declines continuously during cool-down. The conductor with the 55 μm PU thickness has the highest heat transfer peak, close to 27 W/cm², more than 8x higher than the bare conductor heat transfer in this temperature range. Compared with the bare HTS tape at 77K SVP, the recovery time and maximum heat transfer of the coated sample with the 55 μm PU in 65 K subcooled LN2 are 7x shorter and 15x higher, respectively. The large solid circles indicate measurements derived from SNB states encountered during cool-down under load of the HTS wire with 55 μm PU coating, to be described in section 3.4.

Because of its superior heat transfer, a PU coating with thickness 55 μm was selected for the wire for the fault tolerant HTS transformer winding¹⁸.

Solid coatings are effective at extending the range of conductor temperature over which nucleate boiling occurs because they allow the conductor temperature to exceed the temperature of the interface between coating and liquid by the temperature drop across the coating thickness. Considering the peak in nucleate boiling heat transfer, this can be expressed:

$$T_{cond\ pk} = T_{NB\ pk} + d_c q_{NB\ pk} / \kappa_c \quad (3)$$

Where $q_{NB\ pk}$ is the peak nucleate boiling heat transfer, $T_{cond\ pk}$ is the conductor temperature and $T_{NB\ pk}$ is the temperature, assumed constant, of the surface of the coating at peak heat transfer, d_c is the thickness of the coating, and κ_c is its average thermal conductivity. Figure 12 shows the temperature of the peak in heat transfer plotted against $d_c q_{NB\ pk}$. The fit excludes the last point, for the 120 μm coating, which is perhaps affected by transients at the onset of cooling. The points lie on a straight line. The inverse of the slope gives the average thermal conductivity of the coating, assumed constant even though the temperature of the coating at peak heat transfer can be inferred to span a range of about

110 to 160 K for the thinnest coating, up to 110 to 230 K for the thickest. The average thermal conductivity from the slope is 0.19 W/m.K which is in good agreement with typical values for polymers in this temperature range³⁰. The intercept predicts that the conductor temperature at peak heat transfer for a zero-thickness coating should be 108 K, in good agreement with our measurements on non-superconducting tapes.

a. Conductor temperature versus time.

b. Heat transfer during cooling versus conductor temperature (Large solid circles are from recovery current measurements).

Figure 11. Thermal performance of AMSC 8700 type HTS samples with different coating thicknesses immersed in 65 K subcooled LN2.

Figure 12. Dependence of conductor temperature at peak heat transfer on the product of coating thickness and heat transfer at the nucleate boiling peak. The line is a linear fit excluding the last point

While they can significantly increase boiling heat transfer, coatings will reduce the convective heat transfer by adding the thermal resistance of the coating in the heat conduction path. The convective heat transfer coefficient for bare conductors is given by the slope of the curves in Figure 5. A representative value is $h = 800 \text{ Wm}^{-2}\text{K}^{-1}$. The effective conductive heat transfer coefficient for the coating is given by $h_{cc} = \frac{\kappa_c}{d_c}$, with a value around $3400 \text{ Wm}^{-2}\text{K}^{-1}$, assuming a $55 \text{ }\mu\text{m}$ thick coating with conductivity of $0.19 \text{ Wm}^{-1}\text{K}^{-1}$. The ratio of the convective heat flux with coating in place relative to the bare conductor at the same conductor temperature is given by $\frac{q_c}{q_0} = \frac{h_{cc}}{h_{cc}+h}$. The convective heat flux with coating in place is reduced in this case to 81% of that for the bare conductor.

3.4. Recovery under load

Power transformers are expected to continue to operate at rated current after the short circuit fault is isolated. HTS transformer windings need to have, along with high heat transfer, low enough resistance to allow them to cool down to regain the superconducting state while carrying substantial current in the metal stabiliser of the wire.

Figure 13 shows cool-down curves for a 0.3 mm thick copper tape with $55 \text{ }\mu\text{m}$ PU coating in subcooled LN2 at 70 K , 1 bar . The sequence of curves is for increasing current levels flowing during the recovery period, the cool-down interval following the high current heating pulse. For the last curve in the sequence, a high current pulse of 194 A was applied for 1 s , before dropping the current to 10 A to allow recovery. The average power dissipated in the stabiliser during this pulse, 4.75 W/cm^2 , just balanced the heat transfer to the LN2. The measured input power with $\frac{dT}{dt} = 0$ then serves as an independent check on the heat transfer calculated using $VC_{pv} \frac{dT}{dt}$ in Equation (1), which depends on C_{pv} reference data and on the calibration of conductor resistance versus temperature. With the recovery current held constant at a slightly lower level, at 190 A , the copper tape cools down to near the base temperature. The final temperature exceeds the base temperature by an amount proportional to the square of the recovery current. The corresponding heat transfer coefficient of around $600 \text{ Wm}^{-2}\text{K}^{-1}$ is consistent with the convective heat transfer data in Figure 5.

Figure 14 shows the results of recovery current measurements on an HTS tape with $55 \text{ }\mu\text{m}$ PU coating. Below the 90 K critical temperature of the HTS wire, its resistance does not give a reliable measure of conductor temperature. However, the power dissipated at constant current clearly shows when the wire has regained the superconducting state. At recovery currents of 125 A and above, the cool-down “stalls” at tape temperatures between 95 and 110 K . At 110 A recovery

current, the tape resistance corresponds to a temperature below 90 K and is continuing to drop slowly. At 90 A recovery current, the rapid drop in dissipation below a threshold at about 1 W/cm^2 marks the recovery of the superconducting state. The power density plateaux at 125 A and above allow us to estimate the equilibrium nucleate boiling heat transfer points shown in Figure 11; they are in very good agreement with the curve calculated from the free-cooling temperature record. Table 4 summarises the results of the cool-down heat transfer measurements in subcooled LN2 at 65 K, 1 bar, on HTS samples with different coating thicknesses.

Figure 13. Cool-down curves for thick copper tape with $55 \mu\text{m}$ PU coating with current flowing during the recovery period measured in subcooled LN2 at 70 K, 1 bar. The conductor was heated to around 300 K with a 0.33 s duration high current pulse of 925 A, followed by the application of a recovery current as described in the text. The legend gives the recovery current in A.

Figure 14. Input power density as a function of time for an HTS tape with $55 \mu\text{m}$ PU coating during cool-down in subcooled LN2 at 65 K, 1 bar, with recovery current flowing as indicated in the legend.

Table 4. Heat transfer and recovery characteristics of superconducting tape with different thickness coatings in subcooled LN2 at 65 K, 1 bar.

Coating	Nominal thickness of coating (μm)	Free recovery time from 285K (s)	Maximum heat transfer (W/cm ²)
None	0	2.6	3.3
PU	45	0.68	24.5
PU	55	0.7	26.8
PU	100	0.80	23
PU	120	0.85	22.3
Kapton	25	2.0	11.5

Figure 15. Heat transfer in cooling of copper tape in LN2 at 77K SVP: bare tape, with adhesive Kapton wrap, and non-adhesive Nomex paper wrap.

3.5. Effect of wrapped insulation on heat transfer

Wrapped kraft paper is a standard insulation material in conventional oil-immersed power transformers to obtain the insulation levels required for high voltage windings. Both kraft paper³¹ and aramid³² paper wrap have been proposed for HTS transformer insulation. In order to investigate the heat transfer characteristics of wrapped conductors, we prepared samples with Nomex paper and Kapton adhesive tape wrapped on 0.3 mm thick, 5 mm wide copper tape. The Nomex was type 401 paper, 0.05 mm thick, 10 mm in width, and the Kapton thickness was 25 μm. Both were wrapped around the copper wire with 25% lap under 3kg tension.

Figure 15 shows heat transfer during cool-down of a 0.3 mm thick copper tape with different wrapped coating in LN2 at 77 K SVP. Heat transfer with the wrapped Nomex paper insulation is significantly reduced, to less than half that of the bare tape. This is most likely due to the LN2 in direct contact with the tape under the Nomex paper. We hypothesise that the LN2 evaporates during the heating pulse and establishes a gas sheath around the tape that is confined by the paper

wrap and is therefore more stable than the gas film around a bare tape in the film boiling regime. The combination of vapour and paper wrap insulates the tape surface from contact with the LN₂, so that the heat transfer is drastically reduced. In contrast, the wrapped Kapton adhesive tape prevents direct contact of the LN₂ with the tape and allows heat transfer by nucleate boiling, increasing the heat transfer as much as 8x compared to the Nomex paper wrap.

3.6. Effect of one-sided contact with an insulating former on heat transfer

In conventional power transformers the relatively massive copper conductors are partially self-supporting and are typically held in place under tension using a range of pressboard spacers. In HTS power transformers applications, the HTS conductors, with their much smaller cross-section and vulnerability to damage by localised deformation, need to be immobilized by winding under tension on insulating formers or in multilayer pancake coils. Contact under tension with unyielding surfaces with small radius of curvature will damage the wire and must be avoided. Winding formers need to be robust, non-conductive, non-magnetic and ideally have thermal contraction matching that of the HTS tapes. They are usually made of G10 epoxy-glass composite material. In order to resist the large Lorentz forces on the conductors during short circuit or inrush current transients, HTS conductors, particularly high current conductors such as Roebel cables, have been immobilized by mounting them in trenches machined in composite formers²⁹. The problem with this configuration is the reduced heat transfer because only one side of the HTS wire is exposed to the LN₂ and the other side is held in tension against the G10 former. For this reason it is important to measure the effect of the insulating substrate/former on heat transfer. For this purpose, a 0.3 mm thick, 4.8 mm wide copper tape was mounted under 13 kg tension in a 1.5 mm deep, 5 mm wide trench machined circumferentially on outside of a G10 former, external diameter 138 mm, as depicted in Figure 2.

Note that the power values are normalised here by the total surface area of the sample, not by the area of the exposed face of the sample. This means if contact with the substrate entirely eliminates heat transfer on the contact face, then the total surface heat transfer should be halved compared to the free-standing sample.

Plots of stable convective cooling heat transfer versus conductor temperature are shown in Figure 16(a) for both isolated and in-groove copper tape at different LN₂ temperatures in subcooled and SVP conditions. In both SVP and subcooled conditions, the convective heat transfer and the maximum convective heat transfer achievable before the onset of boiling decrease when the conductor is mounted in the groove. In order to quantitatively estimate the reduction, the curves for both free-standing and in-groove conductors were fit, as for the data in Figure 5, with the power law Equation (2). The curves for in-groove heat convection are brought into good agreement with the curves for the free-standing sample using the scaling factors q (in-groove)/ q (free-standing) given in Table 5.

Table 5. Fit parameters for stable convective cooling heat transfer curve for conductors mounted in-groove; in a trench on a glass epoxy composite former.

Fit Parameters for	T0 (K)	a (W/K.cm ²)	δ	Scaling Factor (%)	In-groove $q_{\max}$ (W/cm ²)
SVP 77K	77.3	0.053	0.074	93.6	0.204
Subcooled 70K	70.4	0.032	0.17	62.4	0.475
Subcooled 65K	65.9	0.033	0.15	56.5	0.765

For the conductor in subcooled LN₂, the effect of mounting in the groove is to reduce the convective heat transfer almost by half, to around 62% and 57% for the 70 K and 65 K subcooled liquid respectively, rather than 50%, so a minor

contribution remains from the occluded face of the conductor. In contrast, the convective heat transfer from the conductor at SVP is barely reduced, by only about 6%, by mounting in the trench. It may be that in SVP conditions some local boiling is taking place in the thin layer of liquid confined between the former and the conductor tape to augment the convective heat transfer from the exposed face of the tape.

a. Stable natural convection curves

b. Stable nucleate boiling curves

Figure 16. Plots of (a) stable natural convection and (b) stable nucleate boiling heat transfer versus conductor temperature for 0.3 mm thick copper tapes mounted in a groove on an insulating substrate immersed in LN2 at SVP atmospheric pressure and subcooled situations compared to free-standing tapes

Figure 16(b) shows the heat transfer for SNB as a function of conductor temperature for a 0.3mm thick copper tape in-groove at different LN2 temperatures in the SVP and subcooled condition compared with a free-standing tape. The in-groove and free-standing curves seem to cross. It appears that the degree of superheating to initiate nucleate boiling has been reduced by contact with the composite former – the in-groove curves extrapolate back to close to 79 K, while the free-standing curves appear to originate near 81 K. This is perhaps to be expected since the contact zone between the conductor and former will provide a high density of potential nucleation sites for boiling.

a. Conductor temperature versus time

b. Heat transfer versus conductor temperature

Figure 17. HTS tape samples immersed in subcooled LN2 at 65 K during cool-down: comparison of bare tapes and with 55μm coating; free-standing, and mounted in-groove

Cool-down from temperatures around 300 K was also measured for coated and bare HTS samples mounted in-groove on the composite former. Figure 17(a) compares the conductor temperature versus time for isolated and groove-mounted samples. Cool-down takes longer for in-groove samples, both bare and coated. Although the reduction in cool-down time does not seem great, the corresponding heat transfer curves, shown in Figure 17(b), reveal that the peak heat transfer for the coated tape is roughly halved by mounting on the former. For the bare tape, mounting on the former appears to almost eliminate the nucleate boiling peak, shifting it to lower temperatures around the superconducting transition temperature of the tape.

4. Conclusions

Heat transfer is of fundamental importance to HTS transformer technology. Efficient convective heat transfer is required to ensure that AC loss during normal operation does not raise the conductor temperature enough to significantly reduce the critical current. Boiling heat transfer is important for ensuring rapid cool-down after a fault current has raised the conductor temperature to 300 K or more, including recovery under load with current flowing in the metal stabiliser layers of the HTS conductor. In the case of extended fault current duration, up to 1 s or longer, heat transfer has an important role, along with the thermal mass of the conductor, in limiting the maximum conductor temperature and extending the fault withstand time.

In this paper we report measurements of heat transfer relevant to the design of HTS transformer windings. Our main findings are as follows:

- Importance of subcooling for improving heat transfer and recovery: Subcooling of LN2 significantly increases the boiling heat transfer compared to LN2 at SVP. Thus, sub-cooling is advantageous for HTS transformers not only for the improvement in critical current at lower temperatures and the avoidance of bubbles in normal operation, but also for improving heat transfer and recovery performance.
- Extended nucleate boiling: Conductors with a solid insulation coating with optimized thermal resistance exhibit extended nucleate boiling (ENB). They have much greater boiling heat transfer than bare conductors because the coating surface, insulated from the conductor, stays within the nucleate boiling regime and avoids the lower heat transfer associated with film boiling. The measured conductor temperature at peak nucleate boiling was shown to be consistent with the coating thickness and thermal conductivity of typical polymers in this temperature range. The convective heat transfer with ENB coatings with optimal thermal resistance in place is slightly reduced, by about 20 %, compared to bare surfaces.
- High level of heat transfer achieved by optimized solid coating: Compared with a bare HTS tape in 77 K LN2 at SVP, the recovery time and maximum heat transfer of a coated HTS sample with a PU coating 55 μm thick in subcooled LN2 at 65 K, 1 bar, are 7x shorter and 15x higher respectively. The maximum heat transfer, measured at a conductor temperature close to 200 K, was about 27 W/cm². Because of the enhanced heat transfer, the Type 8700 HTS tape, despite the relatively high resistance of its brass stabilizer, was able to cool down from around 300 K and regain the superconducting state while carrying a recovery current of close to 100 A.
- Limitations of Nomex paper in HTS transformer applications: Conductor tapes with wrapped Nomex paper insulation have very significantly reduced boiling heat transfer compared to bare conductors. This suggests that, for HTS transformer windings, solid insulation should be preferred to the wrapped paper insulation typical of the oil-immersed windings of conventional transformers.
- Effect of mounting on former/substrate: Heat transfer in subcooled LN2 is almost halved by mounting on an insulating substrate. This result suggests that the investigation of multi-layer winding configurations that do not unduly reduce the high boiling heat transfer demonstrated here for free-standing conductors should be a priority.

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