3 Single Strand Tests

In the previous chapter, we observed that the polyimide tape wrapped on the cable for insulation influenced the quench propagation velocity, especially at the current above about 2900 A. In order to examine whether the influence of the polyimide tape would appear only in the Rutherford cable, we measured the quench propagation velocity of a single strand cable.

3.1 Apparatus

The overview of the experimental setup is shown in Fig. 3.1. A strand was removed from an eight-strand Rutherford cable, and it was about 2 m in length. This strand is wound with essentially no overall inductance along a narrow channel grooved on a GFRP bobbin, whose diameter and height are 50 mm and 30 mm, respectively. The pitch of the groove is 3 mm and the total number of turns on the bobbin is 10. This sample holder is fixed in a solenoid so that the center of the bobbin coincides with the magnetic center of the solenoid. The solenoid has the diameter and height of 74.3 mm and 142.5 mm, respectively. The solenoid can be excited up to 5.5 T at the magnetic center. The whole sample is vertically mounted in a 1.3 m long vertical cryostat made of GFRP, and cooled at 4.2 K with pool boiling liquid helium.

For comparison, the quench propagation velocities were measured under three cooling conditions as follows:

- condition A: strand without thermal insulation,
- condition B: strand covered with epoxy for thermal insulation from liquid helium, and
- condition C: strand wrapped with a polyimide tape of 50 μm in thickness and 8

mm in width with 50% overlap.

Fig. 3.2 shows the arrangement of the three conditions and the positions of voltage taps and heaters. The heaters are carbon paste heaters similar to those used in the Rutherford cable tests. Under each cooling condition, the index of the voltage taps are assigned to the numbers from 1 to 5 in the order of the current flow. The numbers in parentheses are the relative distances from heater HT1 or HT3. The measured lengths of the strands of conditions A, B and C are 316 mm, 264 mm and 250 mm, respectively. The magnetic field uniformity of the solenoid in these measurement regions is better than 1%.

The test procedure and data-taking system were almost the same as those for the Rutherford cable tests. The quench propagation velocity was calculated in the same way as in the cable tests, namely, from the difference of the take-off time of voltage tap signals and the distance between voltage taps.

3.2 Test Results

The quench propagation velocities were measured as a function of strand current and external magnetic field produced by the solenoid. We measured the velocities at three magnetic fields; a constant field of 4 T ($B4$), the maximum field on the cable (B_{max}) and the minimum field on the cable (B_{min}). B_{max} and B_{min} are defined in Eqs. (2.3) and (2.4), respectively. The test results are shown in Fig. 3.3. The lower horizontal axis is the strand current, and the upper horizontal axis is the estimated cable current from the strand current. The vertical axis is the average of the quench propagation velocity between voltage taps No.1 and No.5. The heater used was HT1 in condition A, HT3 in condition B and HT5 in condition C. The shapes of symbols represent the magnetic field applied to the strand. The open, closed and gray symbols represent the cooling conditions A, B and C, respectively. As can be seen in this figure, the velocities in conditions A and B were approximately parallel to each other at any magnetic field. On the contrary, in condition C, although the velocities at B_{min} and $B4$ were almost parallel, the velocities at B_{max} increased in the strand current range above 325 A compared with the other cooling conditions.

Figure 3.4 shows the quench propagation velocities at B_{max} as a function of distance from the heater to the center of voltage tap pair. The circle and square symbols are the average velocity at the strand current of 394 A and 325 A, respectively. In conditions A and B, the quench front propagated with almost a constant velocity, although the velocity in condition B at 394 A changed slightly due to the field non-uniformity of the solenoid. However, in condition C, the velocities were different at every position at the strand current of even 325 A. At 394 A, the spread of the velocity at every position became quite large.

The velocities on every pair of voltage taps in condition C at B_{max} are shown in Fig. 3.5. The closed and open circles represent the velocities measured for the quenches induced by heaters HT5 and HT4, respectively. In the case of the opposite direction of quench propagation, the velocities are almost the same at each section.

As described above, the quench propagation in the strand wrapped with a polyimide tape was different from that in the other two cooling conditions. This result is almost the same as in the Rutherford cable tests.

3.3 Influence of Polyimide Tape on Quench Propagation Velocity

From the test results described in the previous section, we can think of the following mechanism about the influence of the polyimide tape. Fig. 3.6 shows the schematic view of the cable cross section in the longitudinal direction. There is a cooling channel between the cable and the polyimide tape, and this cooling channel is filled with liquid helium as shown in Fig. 3.6(a).

In the case of the cable without polyimide tape, once the quench occurs and the temperature of the cable increases, the cable is cooled by liquid helium around the cable. However, in the case of the cable wrapped with polyimide tape, helium gas evaporated near the normal region is hard to be removed, and it will expand in the cooling channel.

If the spreading velocity of helium gas in the cooling channel is higher than the quench propagation velocity, as shown in Fig. 3.6, the cooling channel is filled with helium gas. The temperature of helium gas is always higher than the temperature of liquid helium, and the thermal conductivity of the polyimide tape is very low. Therefore, the cooling effect by helium cannot be expected, and in the worst case the cable is heated up by warm helium gas.

The quench propagation velocity of the cable in an adiabatic condition or surrounded with the warm gas is higher than the velocity of the cable cooled by liquid helium. The spreading velocity of helium gas is decided by the size of cooling channel, the flow rate of liquid helium into the cooling channel, the amount of the Joule heat generation in the normal region, and so on.

In the single strand tests, above the strand current of 325 A, the spread of the quench propagation velocities at every position became large. However, in the Rutherford cable tests, the spread of the velocities at every position became large at the current of one strand of 362.5 A (the cable current was 2900 A). This discrepancy of the threshold currents also seems to be caused by the difference of the cooling channel size, and so on.

A similar phenomenon has been reported as a *thermal hydraulic quenchback* phenomenon [34]-[36] in a cable-in-conduit force-cooled superconducting cable (*CIC cable*), which is used in a superconducting magnetic energy storage (*SMES*) system and a magnet for nuclear fusion, etc.

In order to examine whether this hypothesis is true or not, more detailed experiments are necessary.

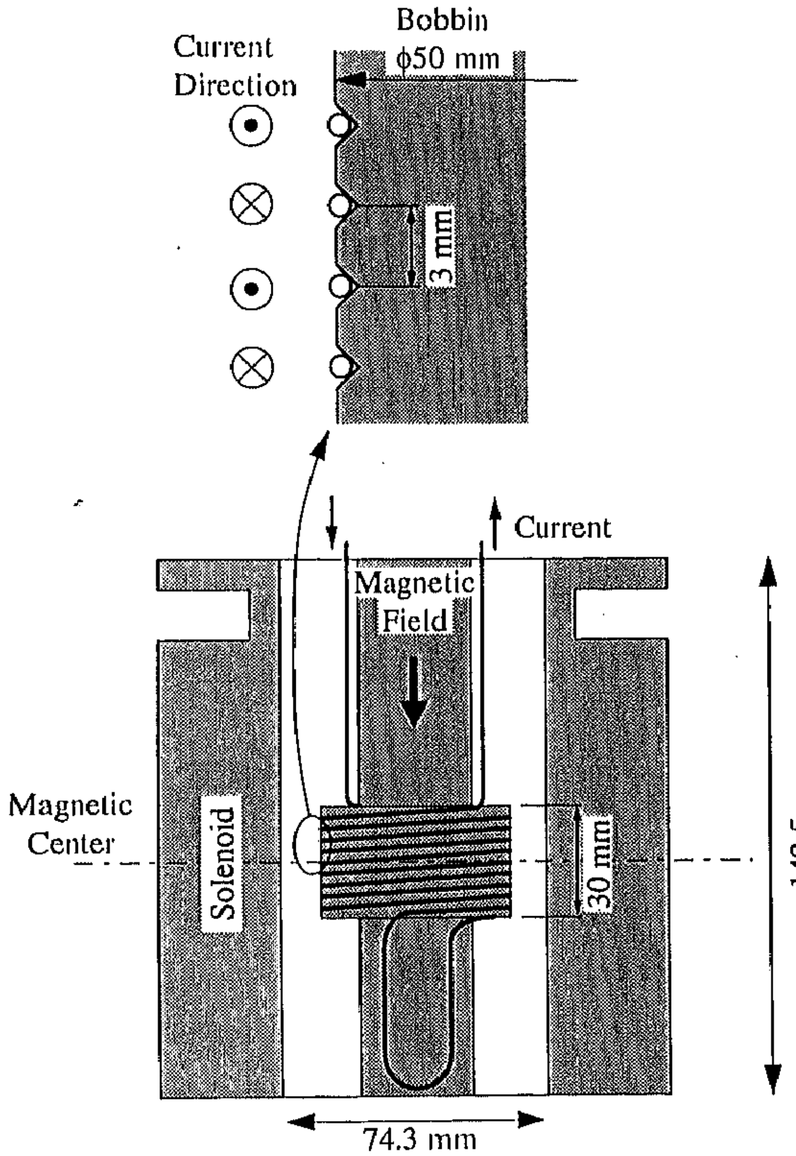

Fig. 3.1: Overview of the experimental setup for the single strand tests.

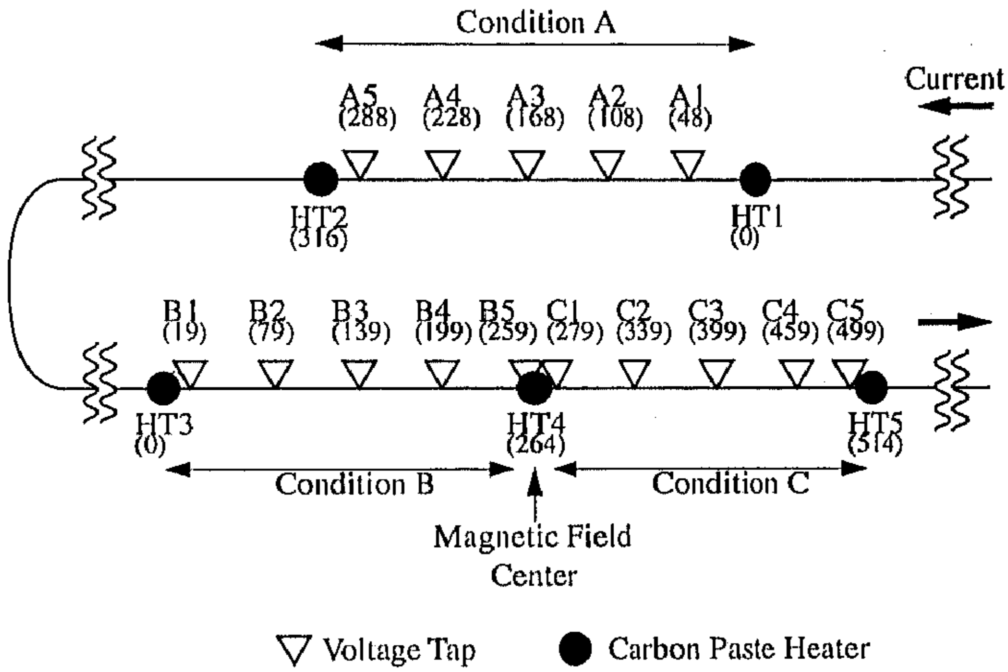

Fig. 3.2: Arrangement of three cooling conditions and positions of the voltage taps and the heaters. Condition A is the strand without thermal insulation, condition B is the strand covered with epoxy for thermal insulation, and condition C is the strand wrapped by polyimide tape with 50% overlap. The numbers in parentheses are the relative distances from heater HT1 or HT3.

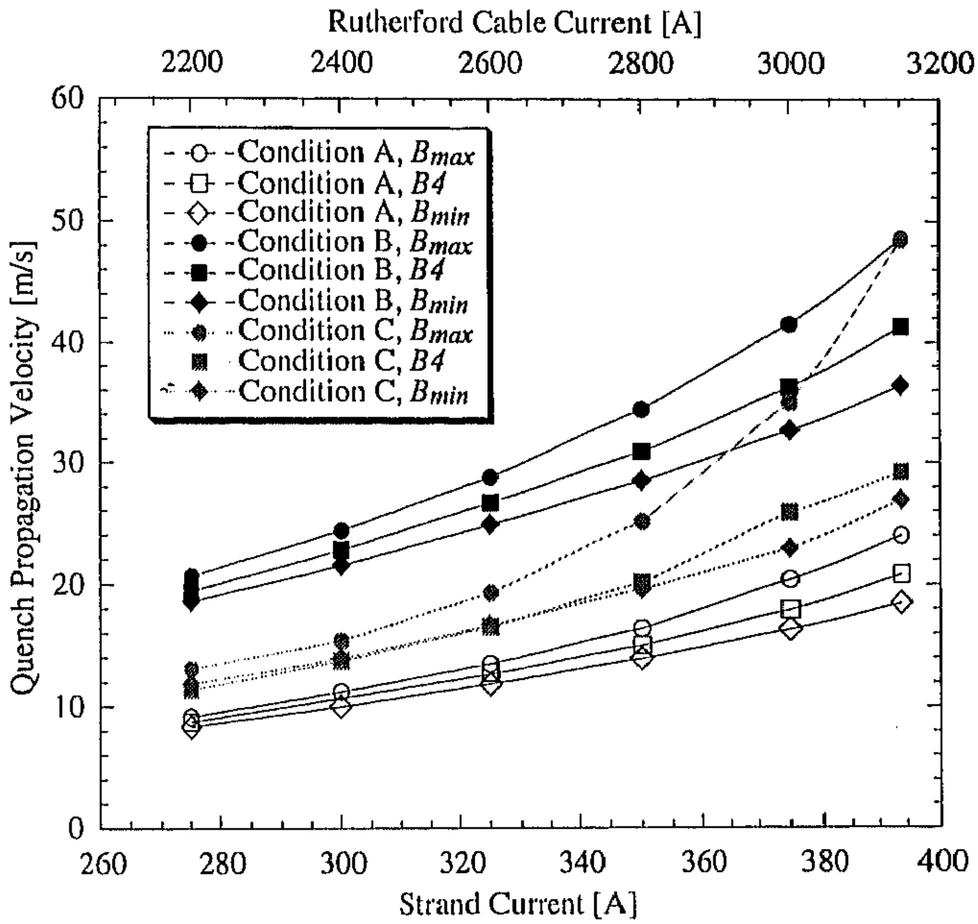

Fig. 3.3: Quench propagation velocities of a single strand measured under three cooling conditions as a function of strand current.

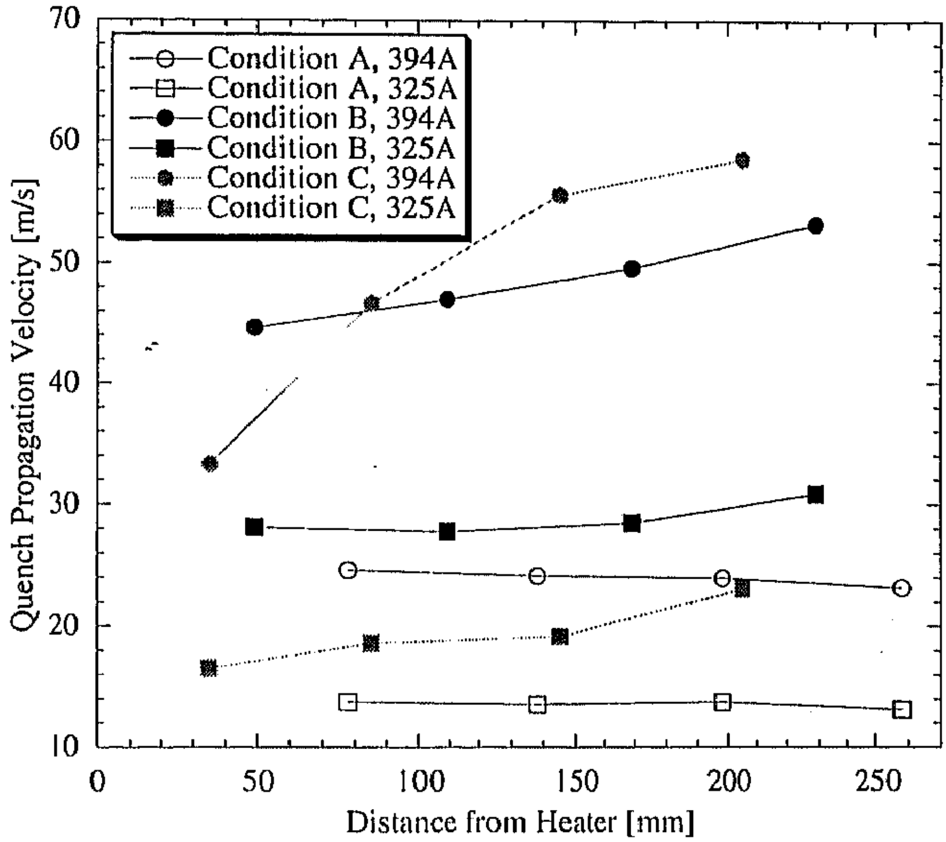

Fig. 3.4: Quench propagation velocities as a function of distance from the heater to the center of voltage tap couple at B_{max}.

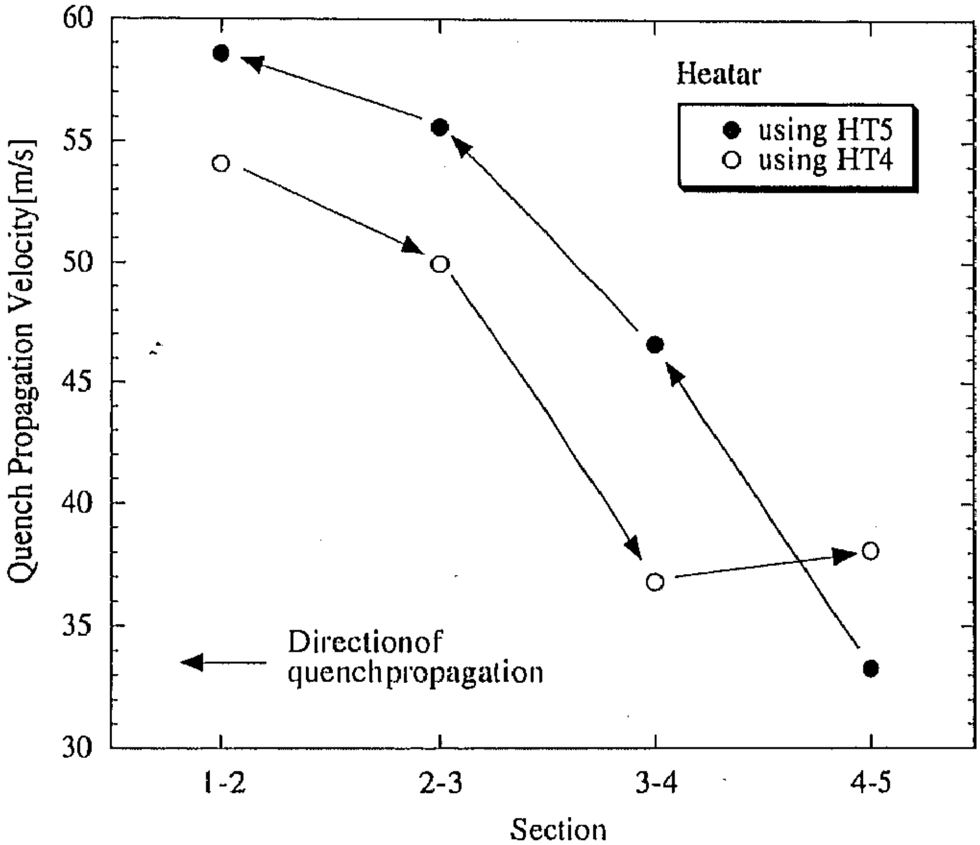

Fig. 3.5: Quench propagation velocities on every pair of voltage taps in condition C at the strand current of 394 A at B_{max}.

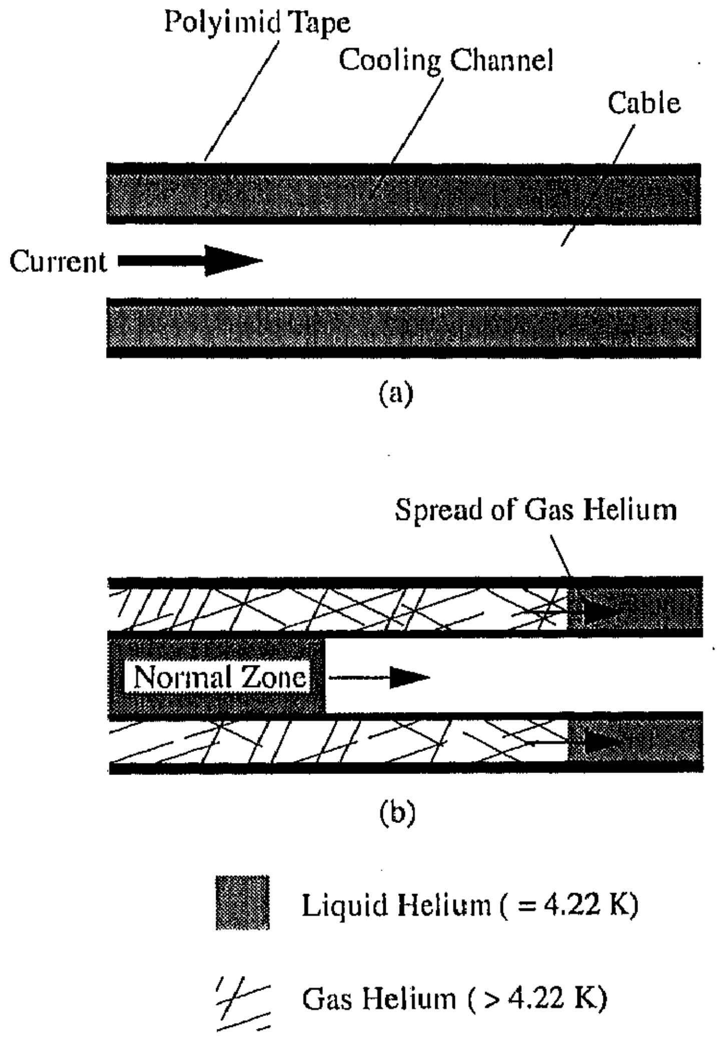

Fig. 3.6: Illustration of helium in a cooling channel around the cable. (a): before quench, (b): during quench propagation.