Nuclear Magnetic Resonance Measurements in Oil-Nitrogen Two-Phase Flow

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NMR measurements of the oil mass flow have been carried out in all-oil flow as well as in oil-nitrogen two-phase flow. For the calibration a simplified method was used which circumvents spin-lattice relaxation calculations due to the short polarization time of the protons at rather high flow velocities. With this method an overall accuracy of the oil-flow in oil-nitrogen two-phase flow of about ±5% was achieved.

Some proposals for an improvement of the NMR apparatus are made, which would render the evaluations simpler and more accurate.

Introduction

Most of the NMR work on flow has been devoted to relatively slow flow for applications to e.g. medicine [1]. In contrast to this we have proposed a new NMR method for fast and highly turbulent flow [2]. The aim of the present paper is the application of this method to measurements of oil-nitrogen two-phase flow. For the measurement we used heating oil AMOCO type 3/5 with dynamic viscosity between 20 and 35 cP and relative density 0.945. This liquid is much more viscous than water and has correspondingly shorter nuclear relaxation times, which influence the measurements and the evaluations.

Some General Considerations on NMR Two-Phase Flow Measurements

Our measurement arrangement is shown in Figure 1. The flow is downwards and consists either of oil or an oil-nitrogen mixture. Our NMR spectrometer is a computer-controlled BRUKER CXP spectrometer. It uses proton resonance and measures only the liquid flow. The magnet has a length of 40 cm in flow direction. Its resonance field $B_0$ of about 0.0939 T (corresponding to our proton resonance frequency of 4 MHz) serves also for the polarization of the spins. Under flow conditions the spins spend on average the polarization time $t_p$ in the magnetic field before they reach the measuring region of the RF coil in the center of the magnet. Hence the nuclear magnetization $M$ parallel to $B_0$ has to be multiplied by a relaxation factor $1 - \exp(-t_p/T_1)$ with $T_1$ being the spin-lattice relaxation time.

In our RF coil the 8 kW transmitter can produce a magnetic RF field $\gamma R F$ with amplitude $2B_1$ as usual. We use a Carr-Purcell-Gill-Meiboom pulse sequence [2-4]. This creates a spin-echo sequence, the envelope of which is, in the absence of flow, proportional to $\exp(-t/T_2)$ with the spin-spin relaxation time $T_2$. If we have flow in addition, the spins originally tilted by the $90^\circ$ pulse, which form the nuclear magnetization $m(t)$ in the direction transverse to the magnetic field $B_0$, will leave the coil physically due to the flow. In this case the echo envelope decreases accordingly in an efflux curve $EFC(t/T_E)$, where the characteristic time $T_E$ is the efflux time [2]. After this time has elapsed, all the observable spins will have left the RF coil and no transverse magnetization can any longer be detected. Thus the transverse magnetization as measured by the echo envelope will have the form

$$m(t) = M_0 \cdot [1 - \exp(-t_p/T_1)] \cdot \exp(-t/T_2) \cdot EFC(t/T_E).$$

Here $M_0$ is the nuclear paramagnetic equilibrium magnetization

$$M_0 = \chi_0 B_0,$$
where

\[ \chi_0 = N \gamma^2 h^2 I (I + 1)/(3 kT) \tag{3} \]

is the static nuclear paramagnetic susceptibility. \( N \) is the number of spins \( I \) in the liquid per volume and \( \gamma \) the magnetogyroscopic ratio of the spins. These equations show that, at least in principle, we can obtain the liquid fraction from the magnetization \( M_0 \), which is proportional to \( N \). The average velocity can be evaluated from the time dependence of the efflux curve. The evaluation procedure has been outlined in [2]. It will be briefly described here:

- At first we assumed idealized conditions with an homogeneous magnetic field \( B_1 \) inside the RF coil of length \( L_c \) in flow direction and zero field outside this coil. Thus the spins tilted by the 90° pulse form a cylinder of length \( L_c \) and the inner diameter of the loop tube. Further we assumed that all the spins exhibit exactly the same velocity \( v \). Thus this whole cylinder of tagged spins will move downstream with this velocity after the 90° pulse. After time \( t \) it will have moved by the distance \( vt \). If we neglect relaxation effects, the echo sequence will then decay as

\[ m(t) = m_0 (1 - vt/L_c) = m_0 (1 - t/T_E) \tag{4} \]

This is a simple efflux curve with the efflux time \( T_E = L_c/v \). After this time, the whole cylinder will have moved out of the RF coil and consequently the echo sequence will have decayed to zero. With a real RF coil we do not have such a nicely shaped \( B_1 \) field, and (4) will no more be valid. If we still assume the same velocity for all the spins, we get

\[ m(t) = m_0 \text{ISC}(t/T_E) \tag{5} \]

instead. The efflux curve is now an iso-speed curve ISC. This is a type of calibration efflux curve which depends on the geometry of the magnetic field. It must be determined experimentally for each specific coil arrangement. We got it by pulling a sealed piece of the loop tube filled with water through our RF coil. This coil is similar to a saddle coil, has as length of 10 cm and consists of six windings arranged round the flow tube in such a way as to obtain a sufficient homogeneity of the \( B_1 \) field over the inner cross-section of the tube [5].

In a real flow situation we have a velocity distribution. To each group of spins with velocity \( v_i \) and corresponding efflux time \( T_{E_i} \) we ascribe a partial magnetization \( m_{0i} \) at the end of the 90° pulse. These partial magnetizations form the velocity probability distribution. Each group of spins with velocity \( v_i \) has further an iso-speed curve ISC\( (t/T_{E_i}) \). The sum of all these iso-speed curves, weighted by the partial magnetizations, is then our measured efflux curve EFC. For the practical evaluation of such an efflux curve in an unknown flow situation we assume a set of \( N_v \) equally spaced efflux times \( T_{E_i} \) according to the time-scale of the EFC. \( N_v \) is the number of spin groups with corresponding velocities \( v_i \). Then we calculate the partial magnetizations \( m_{0i} \) by an iterative computer fit of the sum of the iso-speed curves to the measured efflux.

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Fig. 1. Schematic of NMR flow measurement at a loop tube.
The measurement is accomplished by measuring the echo maxima only. Each spin echo gives one measured value, and with these we obtain the echo envelope, which shows the decay of the transverse nuclear magnetization \( m(t) \) and has the form

\[
m(t) = A_0 \cdot \text{EFC}(t/T_E) \cdot \exp(-t/T_2) = A_{00} \cdot AT \cdot \text{EFC}(t/T_E) \cdot \exp(-t/T_2).
\]

Here \( A_0 \) is the measured signal amplitude immediately after the 90° pulse at the time \( t = 0 \) and \( A_{00} \) is the same amplitude normalized to an attenuation of 0 dB at our receiver attenuator with attenuation \( AT \). This latter is necessary in order to compare measurements of different velocities and hence polarization times and amplitudes. Comparing (1) and (10) we find

\[
A_{00} \sim M_0[1 - \exp(-t_p/T_1)].
\]

In order to obtain the efflux curve, we must first correct our measured curve for \( T_2 \) effects. This can be done either by the known relaxation time \( T_2 \), calculating \( \exp(-t/T_2) \) for each echo and dividing the echo value by it. A better possibility, which we normally apply, is to stop the flow after the measurement, measure the echo envelope without flow at the same time scale as the flow measurement and then correct point by point of the latter by the corresponding points of the experimental \( T_2 \) correction curve. This method works also for liquid mixtures, whose components have different relaxation times \( T_2 \). In this way we obtain the EFC without \( T_2 \) effects, and from this EFC we get the average efflux time \( \langle T_E \rangle \) of the efflux time distribution as described above and in [2].

We assume pseudo-stationary flow conditions to such an extent that the average values of the amplitude \( A_{00} \), efflux time \( T_E \) and velocity \( v \) remain constant over the whole time of the measurement including the polarization time \( t_p \). Under this assumption, and using (9) we can state that

\[
t_p \propto T_E \propto 1/v.
\]

Expanding \( 1 - \exp(-t_p/T_1) \) in a power series up to the third power of \( t_p \), we obtain from (11) and (12)

\[
A_{00}/T_E = A_1 + A_2/v + A_3/v^2.
\]

Now we perform a series of calibration measurements using liquid flow without gas at different velocities and hence different efflux times \( T_E \) and velocities \( v \) measured by the turbine meter. Then we do a least-squares fit of \( A_{00}/T_E \) versus \( v \) according to (13) and thus obtain
the constants $A_1$, $A_2$, and $A_3$. This is shown in Fig. 2, where we have plotted the measured values $(A_{00}/T_E)_{AL}$ in arbitrary units obtained at all-liquid flow versus the velocity $v$. The curve in the figure is the least-squares fit to the data. This ordinate becomes constant at high velocities. This is a great advantage against the direct dependence of the amplitude $A_{00}(v)$, which is varying much more with $v$. It is worthwhile mentioning that, of course, $A_2$ must be negative and

$$A_1 > |A_2| > A_3.$$  \hfill (14)

If (14) is fulfilled, the calibration procedure is reasonable. In the case of Fig. 2 the constants divided by $10^4$ were $A_1 = 11.780$, $A_2 = -6.908$, and $A_3 = 1.106$.

With this preparation we make two-phase flow measurements and obtain, of course, for each measurement a two-phase value $(A_{00}/T_E)_{2P}$ at a certain value of $v$. These two-phase flows exhibit normally high velocities. So we are nearly in the constant part of (13) and can calculate $(A_{00}/T_E)_{AL}$, which we would obtain at all-liquid flow at the same velocity using our fitted constants $A_1$, $A_2$, and $A_3$. The liquid fraction $\varepsilon_l$ is then obtained in a straightforward manner by the ratio

$$\varepsilon_l \equiv \frac{v_{NMR}}{v_{T}} = \frac{(A_{00}/T_E)_{2P}}{(A_{00}/T_E)_{AL}}.$$  \hfill (15)

This approach avoids the determination of the polarization length and $T_1$ correction calculations, which cannot be done reasonably in a flow situation as given in our experiments. It works also for long relaxation times $T_1$, and thus we do not need the addition of paramagnetic species in order to shorten $T_1$. This method is a technical approach in order to obtain meaningful values of $\varepsilon_l$ with an accuracy which is sufficient for technical purposes.

From our all-liquid flow measurements we can obtain the mean velocity $v$ in our measuring section using the liquid mass flow measurement by the turbine at the loop before the liquid gas mixing device. This velocity can be used to get the effective length $L_{fe}$ of the $B_1$ field in the RF coil by (9). This length depends slightly on the velocity because of the change in the turbulence and of the influence of this turbulence on the $T_E$ measurement. This $T_E$ dependence is weak. We therefore make an ansatz as (13) and write

$$L_{fe} = L_1 + L_2/v + L_3/v^2.$$  \hfill (16)

This ansatz is not as well-founded as (13), but it is justified by the results, as can be seen by Fig. 3, which is the velocity calibration curve of a set of all-liquid measurements. It shows the velocity obtained by NMR $v_{NMR} = L_{fe}/T_E$ corresponding to (9) versus the velocity $v_T$ obtained by the oil mass flow measured by the turbine at the oil input to the loop. These measurements have been done with the closed circular loop, as is usual for calibration measurements. It was the same set of measurements as shown in Figure 2. After this we opened the loop and did measurements of the velocity $v$ and amplitude $A_{00}$ with oil-nitrogen two-phase flow. Such measurements can only be done with the open-ended loop, because only then we can measure the mass flows of oil $MF_1$ (liquid) and nitrogen $MN_2$.
MF\textsubscript{g} (gas) before the mixing of both in a reasonable way. The oil-nitrogen mixture is then discharged after each measurement and the next measurement is done with a fresh mixture.

We always used fluctuation averaging by adding efflux curves together point by point. At all-oil flow (Fig. 3) we used 35 addings at low and up to 150 added curves at high velocities. At two-phase flow these numbers are 70 to 150. Such an adding of efflux curves improves on the signal-to-noise ratio S/N as well as on the signal-to-fluctuation ratio S/F caused by the flow. In our case, since we know the mass flow MF\textsubscript{f} = MF\textsubscript{T} at the input into the loop, we can calculate the liquid fraction by the continuity equation. If \( v_T \) would be the velocity at all-oil flow and \( v_{\text{NMR}} \) the oil velocity at oil-nitrogen two-phase flow we obtain

\[ \varepsilon_v = \frac{v_T}{v_{\text{NMR}}} \cdot (17) \]

The comparison of \( \varepsilon_{\text{NMR}} \), (15), and \( \varepsilon_v \) is given in Figure 4. All the values shown lie within \( \pm 5\% \) of the exact value \( \varepsilon_{\text{NMR}} = \varepsilon_v \), shown by the bold line. But at lower liquid fractions we have systematic deviations with \( \varepsilon_{\text{NMR}} < \varepsilon_v \), which are probably due to two effects which take place particularly at annular flow and, since the heating oil has a viscosity of about 28 times that of water, they become more important with oil than with water flow. The critical velocity, which corresponds to the critical Reynold's number, amounts to about 6 cm/s for water and to about 160 cm/s for heating oil in our loop tube. In annular flow with oil the mixing of the spins due to turbulence of the flow during the polarization time \( t_p \) is therefore much weaker than in the case of water. We could not calculate this mixing effect, because we could not make calibration measurements with annular flow. That would have meant using two concentric loop tubes with the correct diameter ratio and with the oil flowing between the inner and the outer tube only. The result of this lack of mixing is, that the slower protons have a longer polarization time \( t_p \) and hence a larger amplitude than the fast ones. The efflux time distribution, which we use for the calculation of the velocity, is therefore shifted to longer efflux times \( T_E \), and hence the velocity is given too small a value. The result is that \( \varepsilon_v \) comes out too large as compared with \( \varepsilon_{\text{NMR}} \), which is exactly what we observe in Figure 4. This effect could be made smaller and the measurements therefore improved if we could install a long polarizing magnet before our measuring magnet. The polarizing field \( B_p \) does not need to be very large, since the NMR signals are large anyway, nor does it need a good homogeneity. But it is absolutely necessary that it has a sufficient physical length along the loop tube in order to obtain a long polarization time during which all the spins are completely mixed and hence would all be polarized in the same way. For our loop the length of the polarizing magnet should at least be 2 m.

A second disturbing effect is the inhomogeneity of the \( B_1 \) field, because in annular flow all the oil is near the wall of the tube, where \( B_1 \) is smaller than in the center, where the gas is flowing. The average efflux time and velocity of the oil are thus averaged somewhat differently at all-liquid and at liquid-gas flow. The remedy for this effect would be to enlarge the RF coil diameter. As \( B_1 \) in our case is by about 10% smaller at the tube wall than in the center, it would be only 0.6% smaller if we enlarged the diameter of the RF coil by 1.4 [5]. This would lower the signal and the signal-to-noise ratio by a factor of two. But this is not a serious problem because the NMR signals from such large coils are very large indeed. The accuracy of the measurement is not determined by the signal-to-noise ratio S/N but rather by the signal-to-fluctuation ratio S/F due to the fluctuations of the flow.

Since the systematic deviations shown in Fig. 4 are only about \(-5\% \) we can correct them by an additional table in our computer program, and the result
Table 1. Results of two-phase flow measurements.

<table>
<thead>
<tr>
<th>$\theta$/$^\circ$C</th>
<th>21.3</th>
<th>21.5</th>
<th>21.5</th>
<th>21.6</th>
<th>21.6</th>
<th>21.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{NW}$/bar</td>
<td>3.2</td>
<td>3.2</td>
<td>2.7</td>
<td>2.6</td>
<td>2.6</td>
<td>2.3</td>
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<tr>
<td>$MF_{N}$/l/min</td>
<td>158</td>
<td>160</td>
<td>161</td>
<td>161.5</td>
<td>163</td>
<td>163.5</td>
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<tr>
<td>$MF_{O}$/l/min</td>
<td>253.4</td>
<td>117.9</td>
<td>84.7</td>
<td>61.3</td>
<td>36.4</td>
<td>17.0</td>
</tr>
<tr>
<td>liquid $v_{loop}$</td>
<td>0.384</td>
<td>0.576</td>
<td>0.655</td>
<td>0.725</td>
<td>0.817</td>
<td>0.906</td>
</tr>
<tr>
<td>fractions $e_{v}$</td>
<td>0.604</td>
<td>0.702</td>
<td>0.770</td>
<td>0.849</td>
<td>0.920</td>
<td>0.990</td>
</tr>
<tr>
<td>$e_{NMR}$</td>
<td>0.579</td>
<td>0.666</td>
<td>0.736</td>
<td>0.832</td>
<td>0.934</td>
<td>0.939</td>
</tr>
<tr>
<td>$v_{NMR}$(m/s)</td>
<td>3.15</td>
<td>2.74</td>
<td>2.52</td>
<td>2.29</td>
<td>2.13</td>
<td>1.99</td>
</tr>
<tr>
<td>$MF_{NMR}$(l/min)</td>
<td>151.4</td>
<td>151.9</td>
<td>154.0</td>
<td>158.3</td>
<td>165.5</td>
<td>155.1</td>
</tr>
<tr>
<td>$MF_{NMR}/$MF$_{O}$</td>
<td>0.96</td>
<td>0.95</td>
<td>0.96</td>
<td>0.98</td>
<td>1.02</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Values of liquid phase (oil)

<table>
<thead>
<tr>
<th>$e_{v}$</th>
<th>0.570</th>
<th>0.671</th>
<th>0.744</th>
<th>0.830</th>
<th>0.909</th>
<th>0.988</th>
</tr>
</thead>
<tbody>
<tr>
<td>fractions $e_{NMR}$</td>
<td>0.572</td>
<td>0.659</td>
<td>0.730</td>
<td>0.827</td>
<td>0.930</td>
<td>0.938</td>
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<tr>
<td>$v_{NMR}$(m/s)</td>
<td>3.34</td>
<td>2.87</td>
<td>2.61</td>
<td>2.34</td>
<td>2.16</td>
<td>1.99</td>
</tr>
<tr>
<td>$MF_{NMR}$(l/min)</td>
<td>158.8</td>
<td>157.2</td>
<td>158.4</td>
<td>160.9</td>
<td>167.0</td>
<td>155.2</td>
</tr>
<tr>
<td>$MF_{NMR}/$MF$_{O}$</td>
<td>1.01</td>
<td>0.98</td>
<td>0.98</td>
<td>1.00</td>
<td>1.02</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Corrected values of liquid phase (see text)

<table>
<thead>
<tr>
<th>$e_{v}$</th>
<th>0.43</th>
<th>0.34</th>
<th>0.27</th>
<th>0.17</th>
<th>0.07</th>
<th>0.06</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{NMR}$(m/s)</td>
<td>7.1</td>
<td>4.2</td>
<td>3.8</td>
<td>4.3</td>
<td>6.3</td>
<td>7.4</td>
</tr>
<tr>
<td>$v_{NMR}/v_{NMR}$</td>
<td>2.1</td>
<td>1.4</td>
<td>1.4</td>
<td>1.8</td>
<td>1.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Calculated values of gas phase (nitrogen)

of this procedure is also shown in Fig. 4, where we have used no correction of the all-oil flow and about +6% for the velocity at low $e_{v}$, with linear interpolation in between. The corrected values are the open circles. Thus the overall accuracy of $e_{NMR}$ seems now even better than $\pm 5\%$.

Our results of measurements in two-phase flow are summarised in Table 1. The first two lines give the temperature $\theta$ in $^\circ$C and the pressure $p$ in bar abs at the measuring section of the loop. The next lines give the liquid mass flow $MF_{L}$ in l/min measured by the turbine and the gas mass flow $MF_{G}$ also in l/min measured by the MKS type 558 A mass flow meter before the mixing of both. There follow three liquid fractions $e_{v}$, $e_{NMR}$ and $v_{NMR}$ as described in the text. Then we give the liquid velocity $v_{NMR}$ and the mass flow obtained by $v_{NMR}$ and $e_{NMR}$. The last line of this first part of the table shows the ratio $MF_{NMR}/MF_{O}$, which gives directly the accuracy of the NMR measurement. The next part of the table shows the corrected values of the last five lines as described in the text. The correction is done at the velocity $v_{NMR}$, therefore $e_{v}$ is changed accordingly but $e_{NMR}$ changes only slightly. At the end of the table we give calculated values of the gas flow. The errors given correspond to $\pm 5\%$ error in $e_{NMR}$. At low liquid fractions the gas flows considerably faster than the oil and we have a slip in the order of two (last line of Table 1). At higher $e_{NMR}$ the gas fraction $e_{g}$ becomes very inaccurate because it has the same absolute error as the liquid fraction. Correspondingly we get large errors in the gas velocity and in the slip. The values and errors given here are certainly consistent with the assumption of no slip at these high liquid fractions.

Conclusions

We could show that the NMR mass flow measurement method developed in this laboratory can be applied to oil-nitrogen two-phase flow. In order to avoid unsuitable spin-lattice relaxation time corrections, we developed an approach via some constants due to the power series of $1 - \exp(-1/T)$, which works very well. We used time-averaging of the NMR signals in order to measure the average liquid mass flow in oil-nitrogen two-phase flow. This liquid mass flow shows a systematic deviation of $-5\%$ at low liquid fractions. This is due to insufficient mixing of the nuclear spins during the polarization period of the measurement and to the inhomogeneity of the $B_{1}$ RF field. It can be accounted for by a correction data base in the evaluation program of the spectrometer computer. The final overall accuracy of the NMR oil mass flow thus obtained is better than $\pm 5\%$.

Acknowledgements

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Nomenclature

$A_{0}$ maximum measured amplitude at beginning of an echo sequence, (10)
$A_{00}$ same amplitude normalized to attenuation 0 db, (10)
$(A_{00}/T_{E})_{AT}$ maximum value of $A_{00}/T_{E}$ corresponding to all-oil flow, (13)
$(A_{00}/T_{E})_{2p}$ value of $A_{00}/T_{E}$ at two-phase flow
$A_{1}$, $A_{2}$, $A_{3}$ polynomial constants of $A_{00}/T_{E} (1/c)$, (13)
$AT$ attenuation at receiver input
$B_{0}$ static magnetic field for NMR
$B_{p}$ static magnetic field for polarization
\( B_{RF} \) magnetic RF field
\( B_1 \) half the amplitude of \( B_{RF} \)
EFC efflux curve, (1), (6) and (10)
\( I \) nuclear spin
ISC iso-speed curve, (5) and (6)
\( L_c \) length of RF coil, (4)
\( L_{te} \) effective length of \( B_1 \) field, (9)
\( L_{1}, L_{2}, L_{3} \) polynominal constants of \( L_{te}(1/t) \), (16)
\( M \) nuclear paramagnetic magnetization parallel to \( B_0 \)
\( M_0 \) thermal equilibrium value of \( M \), (2)
\( MF_g \) gas mass flow
\( MF_l \) liquid mass flow
\( MF_T \) liquid mass flow determined by turbine flow meter
\( MF_{NMR} \) liquid mass flow determined by NMR
\( m(t) \) nuclear magnetization perpendicular to \( B_0 \), (1), (4), (5), and (10)
\( m_0 \) maximum value of \( m(t) \), (4), (5), (6), and (7)
\( m_{0i} \) same for all the spins of velocity \( v_i \), (6), (7), and (8)
\( p \) pressure in bar abs. at test section
\( RF \) radio frequency
\( S/N \) signal-to-noise ratio
\( S/F \) signal-to-fluctuation ratio
\( T_1 \) spin-lattice relaxation time, (1)
\( T_2 \) spin-spin relaxation time, (1)
\( T_{E} \) efflux time, (1), (4), (8), and (9)
\( \langle T_{E} \rangle \) average efflux time, (6) and (8)
\( T_{Ei} \) efflux time of spin group \( i \)
\( t_p \) polarization time, (1)
\( v \) velocity, used also for mean velocity obtained by EFC, (9)
\( \langle v \rangle \) average velocity, (9)
\( v_i \) velocity of spin group \( i \)
\( v_{NMR} \) velocity determined by NMR
\( v_T \) velocity determined by turbine flow meter
\( \gamma \) magnetogyroscopic ratio, (3)
\( \varepsilon \) any fraction of bulk matter
\( \varepsilon_g \) gas (void) fraction
\( \varepsilon_l \) liquid fraction
\( \varepsilon_{loop} \) liquid fraction obtained by loop input data
\( \varepsilon_{NMR} \) liquid fraction obtained by \( (A_00/T_{E})p \), (15)
\( \theta \) liquid fraction obtained by \( v_{NMR} \), (17)
\( \Theta \) temperature in \( ^{\circ}C \) at test section
\( x_{0} \) static nuclear paramagnetic susceptibility, (3)