Dynamic NMR Microscopy

動態核磁顯微成像

VOLUME I

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by

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Abstract

The theory and practice of Dynamic NMR Microscopy are described in detail. The description consists of a brief presentation of **k**-space imaging which includes the 2-D filtered back-projection (PR) reconstruction algorithm as well as the influence of various image contrast factors, a detailed discussion of **q**-space imaging which employs the Pulsed-Gradient Spin-Echo (PGSE) sequence and a thorough description of Dynamic NMR Microscopy which combines both **k**-space and **q**-space mapping. The velocity and self-diffusion image artifacts and errors associated with Dynamic NMR Microscopy have also been investigated extensively.

As part of this work, various modifications to and developments of the existing imaging system have been made. These include the probe design for 'non-trivial' flow imaging experiments and software programming using assembly, BASIC, FORTRAN and PASCAL languages. Several instrument-related issues in NMR microscopy have also been investigated. They include the attempt to improve spatial resolution by scaling down the receiver coil, the zero-frequency 'glitch' artifact in images and the effect of induced eddy current in imaging experiments.

The results of the comprehensive water capillary flow experiments have shown that simultaneous measurement of velocity and self-diffusion coefficient can be made both accurately and precisely using Dynamic NMR Microscopy. Imaging experiments which investigate molecular motion of relevance to plant physiology, fluid dynamics and polymer physics have been carried out. In the *in vivo* botanical studies, velocities of approximately 10 μm/s in the castor bean experiment and 45 μm/s in the *Stachys* experiment have been measured. In the rheological studies, induced secondary flow (eddy) around the abrupt junction in a tube was observed, which has agreed well with numerical simulation of the Navier-Stokes equation. In the studies of unusual rheological properties of high molar mass polymer solutions, velocity profiles for WSR301 polyethylene oxide (PEO)/H_2O in capillary flow were measured and fitted using the power law model. The measurement of self-diffusion profiles for monodisperse PEO standards in D_2O has shown clear evidence for the breakdown of molecular entanglements in semi-dilute solutions once the shear rate exceeds the equilibrium tube renewal rate, τ_d^{-1}.

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List of Symbols

a	RF coil radius	34
a_m	Complex admixture amplitudes of a spin system	6
$\mathbf{B}$	Magnetic field	5
B_0	Amplitude of the main magnetic field	5
B_1	Amplitude of the transverse rf field $\mathbf{B_1}(t)$	10
$\mathbf{B_1}(t)$	RF field (in the transverse plane)	10
c	Concentration	282
c_p	Specific heat at the constant pressure	88
c^*	Critical concentration	282
D	Self-diffusion coefficient	40
D_s	Centre-of-mass self-diffusion coefficient	282
D_0	Zero concentration self-diffusion coefficient	289
$\mathbf{D}$	Self-diffusion tensor	54
$E(m)$	Energy eigenvalues of a spin system	6
$E_c(\mathbf{r})$	Normalized contrast factor	36
$E(\mathbf{g},\delta,\Delta)$	Echo signal amplitude	54
f_0	Resonant frequency	34
F	Noise figure of an instrument	16
$F[\ ]$	Fourier transform of the function in [ ]	60
$\mathbf{g}$	Field gradient in $\mathbf{q}$ space	53
g_m	Maximum gradient employed in dynamic imaging	63
$\mathbf{G}$	Field gradient	23
$\mathcal{H}$	Hamiltonian operator	5
I	Spin quantum number	5
$\mathbf{I}$	The dimensionless spin angular momentum operator	5
I_e	Induced eddy currents	175
I_z	The z component of $\mathbf{I}$	5
j	90° shift of the phase	102
k	Thermal conductivity of the fluid	88
$\mathbf{k}$	Static reciprocal space vector	27
k_B	Boltzmann constant	9
k_{FWHM}	Digital self-diffusion coefficient value	64
k_v	Digital velocity value	64
l	Length of the capillary tube	89
L	Length of the conductor	16

m	Azimuthal quantum numbers	6
M	Molar mass of macro-molecules	278
$\mathbf{M}$	Macroscopic magnetization vector	8
M_n	Number-averaged molar mass of macro-molecules	279
M_w	Weight-averaged molar mass of macro-molecules	279
M_0	Magnitude of $\mathbf{M}$ in the equilibrium state	9
$M_\perp$	Transverse component of $\mathbf{M}$	12
n_D	Maximum number of q slices in addition to the $\mathbf{q}$=0 slice	61
N	Number of spins per unit volume	8
N_p	Number of projections	34
N_{acc}	Number of accumulations per projection	34
p	Perimeter of the conductor	16
P_s	Self-correlation function of the nuclear spin	54
P*	Filtered profile	32
$\mathbf{q}$	Dynamic reciprocal space vector	56
Q	Quality factor of the coil	159
$\mathbf{r}$	Static displacement (position vector)	22
$\mathbf{R}$	Dynamic displacement	55
Re	Reynolds' number	254
$S(\mathbf{k})$	Signal in $\mathbf{k}$ space	28
S(t)	Time domain signal	27
$S(\mathbf{k})^*$	Complex conjugate of $S(-\mathbf{k})$	28
t_p	Duration of the pulse	12
T	Absolute temperature of a spin system	9
T_c	Coil temperature	16
T_e	Entrance temperature of the fluid	90
T_E	Echo time	37
T_R	Repetition time	37
T_w	Temperature at the wall of the capillary	90
T_1	Spin-lattice (or longitudinal) relaxation time	12
T_2	Spin-spin (transverse) relaxation time	12
Tr( )	Trace of the operator in ( )	8
U(t)	Evolution operator	6
$\mathbf{v}$	Velocity	57
γ	Gyromagnetic ratio	5
δ	Duration of the PGSE pulse	52
δ_i	Chemical shift	38

δ	Delta function	60
Δ	Separation of the PGSE pulses	52
η	Dynamic viscosity of the fluid	88
η_0	Zero-shear viscosity of the fluid	281
λ	**q**-space attenuation factor	85
μ	Magnetic dipole moment	5
μ_r	Relative permeability	39
μ_0	Absolute permeability (of free space)	39
ν	Kinematic viscosity of the fluid	252
ρ	Density matrix operator	7
ρ	Density of the fluid	88
ρ_T	Resistivity of the conductor	16
$\rho(\mathbf{r})$	Nuclear spin density	27
σ	RF coil proximity factor	16
σ_t	Thermal noise power	16
σ_{xy}	Shear stress	280
τ	Short time interval	18
τ_d	Tube renewal time of macro-molecules	280
ϕ	Rotation angle of the magnetization vector	12
Φ	Stream function of the fluid	254
χ_m	Magnetic susceptibility	39
ω	Larmor precession frequency	6
ω	Vorticity of the fluid	254
ω_0	Larmor precession frequency due to B_0	11
ω_1	Larmor precession frequency due to B_1	11
ΔE	Energy difference between two adjacent eigenstates	6
Δf	Bandwidth of the receiver	16
Δh	Height difference	89
ΔP	Pressure difference along the length of the tube	89
Δv_s	Velocity spread within one pixel	79
Δx	Transverse resolution	34
Δz	Slice thickness	26
$\Delta\delta$	Difference of chemical shifts	39
$\Delta\phi$	Angle increment size in imaging experiment	32
$\hbar$	Planck's constant divided by 2π	5
$\dot{\gamma}$	Shear rate	280