Diseño e implementación de un prototipo basado en imanes tipo Halbach para la caracterización de flujos multifásicos por medio de Resonancia Magnética Nuclear en el dominio temporal.

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Resumen

Si bien los flujos multifásicos o multicomponentes están presentes en un gran número de procesos, las metodologías existentes para la determinación de las propiedades del flujo presentan grandes limitaciones. En la industria petrolera, por ejemplo, los dispositivos actuales no son capaces de determinar la velocidad del fluido y las fases que lo componen simultáneamente, y no pueden ser utilizados en todo el rango de caudales, proporciones de fases, regímenes de flujo y tipos de petróleo existentes en la industria.

La resonancia magnética nuclear (RMN), técnica no invasiva y de gran versatilidad, aparece entonces como una buena candidata para superar los problemas actuales en la caracterización de flujos complejos. A pesar de sus excelentes cualidades, las técnicas de RMN existentes se basan en su gran mayoría en el uso de gradientes de campo pulsados, lo que involucra requerimientos en el espectrómetro muchas veces difíciles de cumplir. Además, los dispositivos usuales basados en imanes superconductores no facilitan su instalación en la línea de producción y en lugares de condiciones adversas como pozos y yacimientos.

En este trabajo se presenta el desarrollo de una metodología en la cual la velocidad, caudal y la fracción de componentes en el fluido son determinados de manera simultánea y en tiempo real, sin la aplicación de ningún tipo de gradiente de campo magnético estático o pulsado, y que puede ser implementada por medio de espectrómetros de baja resolución. La misma se basa en el estudio de los primeros ecos de una secuencia CPMG, que, para tiempos mucho más cortos que el tiempo de relajación T_2 de cada fase en el fluido, presentan un comportamiento lineal en función del tiempo. La metodología puede ser utilizada en flujos tanto del tipo turbulento como laminar, y en flujos cuya velocidad cambia rápidamente. En una etapa inicial la metodología fue desarrollada para fluidos monofásicos y bifásicos, compuestos por agua y petróleo, pero su extensión a la presencia de aire o gas en el fluido es discutida a lo largo de la tesis. Así mismo, se construyó un prototipo basado en un imán principal del tipo Halbach, construido con bloques de imanes permanentes y dos etapas de pre polarización cuya longitud efectiva puede ser variada, situadas a cada lado del imán principal de manera de permitir la medición de flujos bidireccionales. En el imán principal se implementó una metodología de compensación térmica con el fin de reducir la variación de la magnetización con la temperatura. Además, con el objeto de aumentar la relación señal ruido y posibilitar la producción de imágenes, se realizó un proceso de homogenización del campo magnético, mediante diferentes piezas de materiales ferromagnéticos blandos. Gracias a este proceso la homogeneidad del campo magnético interior al imán principal aumentó en un 80% definiendo una región de interés (RDI) cilíndrica de 10 cm de diámetro y 10 cm de longitud.

Utilizando el método descripto y el prototipo desarrollado se realizaron calibraciones de la velocidad promedio y de la fracción de fases de diferentes mezclas de petróleo y agua, circulando a velocidades tan altas como 2.74 m/s y en rangos extremos del contenido de agua. Se obtuvieron coeficientes de correlación cuadrática mayores a 0.99, residuos menores al 3.5% en la velocidad y menores al 2% para cortes de aceite altos, encontrándose residuos mayores para cortes de petróleo menores al 10%.

Finalmente, mediante técnicas de codificación en fase pura, se realizaron imágenes en 2D de la sección transversal al conducto, utilizando portamuestras de diferentes geometrías y flujos de petróleo y agua. Para esto se debió diseñar y construir un conjunto de bobinas de gradientes especiales para la aplicación en campos magnéticos transversales. Por último, realizando una imagen de cada eco en la secuencia CPMG, y estudiando el decaimiento en cada pixel, se realizaron algunas imágenes de la distribución de velocidades de un flujo en la sección transversal al conducto, obteniendo resultados prometedores para ésta innovadora metodología.

Abstract

Despite the presence of multiphase flows in a large number of processes, the actual methodologies for the determination of the properties of flows have major limitations. In the petroleum industry, for example, the existing devices are not able to determine the fluid velocity and its phases fractions simultaneously, and can´t be used throughout the range of flow rates, cuts, flow regimes and types of existing oil in the industry.

Nuclear magnetic resonance, a noninvasive and highly versatile technique, appears as a good candidate to overcome the existing problems in the characterization of complex flows. Despite its excellent properties, the existing techniques that determine the properties of a fluid by NMR are based mostly on the use of pulsed field gradients, which involves requirements for the spectrometer often difficult to achieve. On the other hand, conventional NMR devices based on superconducting magnets; do not facilitate the installation of the spectrometers on the production line or in places with adverse conditions such as wells and reservoirs.

In this work, it is presented the development of a methodology in which the velocity, flow rate and the fraction of components in the fluid are determined simultaneously and in real time, without applying any static or pulsed magnetic field gradient, that can be applied in low-resolution spectrometers. It is based on the study of the first echoes of a CPMG sequence, which, in times much shorter than the relaxation time T_2 of each phase in the fluid, have a linear function of time, as the fluid leaves the sensing coil. The methodology can be used in both: turbulent and laminar flow, and in flows whose velocity changes rapidly. In an early stage, the methodology was developed for two-phase fluid composed of water and oil, but its extension into the presence of air or gas in the fluid is discussed throughout the thesis.

Also, a prototype was design and constructed. It has a main magnet of the Halbach type, built with blocks of permanent magnets of different sizes, and two stages of pre polarization whose effective length can be varied, positioned on either side of the main magnet in order to allow measuring bidirectional flows. In the main magnet, a thermal compensation method to reduce the variation of magnetization with temperature, was implemented. In order to increase the SNR and enable the production of images, a process of homogenization of the magnetic field was implemented, using different types of magnetic materials, taking advantage of its magnetic qualities and shapes. Through this process the magnetic field homogeneity inside the main magnet increased by 80% by defining a cylindrical region of interest (ROI) of 10 cm diameter and 10 cm in length.

Using the methodology and the prototype developed, calibrations of the average velocity and the fraction of phases of different mixtures of oil and water were made, traveling at speeds as high as 2.74 m/s in extreme ranges of water content. We obtained in all cases correlation coefficients greater than 0.99, residues less than 3.5% in speed and less than 2% for high oil cuts, finding some residues higher for petroleum cuts under 10%.

Besides, using phase encoding technique, 2D images of the cross section of the duct were performed, using different phantoms and petroleum and water flows. For this purposed, a set of special gradient coils for using in transverse magnetic fields geometry were designed and constructed. Finally, performing an image of each echo in the CPMG sequence and analyzing the decay of each pixel, images of the distribution of velocities in the transversal section of a fluid flow were constructed, obtaining encouraging results for this new technology.

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I. Anexo I

Publicaciones relacionadas al trabajo de tesis.

a. Publicaciones en revistas

- Osán, T.M.; Ollé, J. M.; Carpinella, M.; Cerioni, L. M. C.; Pusiol, D. J.; Appel, M.; Freeman, J. y Espejo, I. "*Fast measurements of average flow velocity by Low-Field ^{1}H NMR*". Journal of Magnetic Resonance, 2011. **209**(2): p. 116-122.

b. Patentes otorgadas y provisorias

- Pusiol, D.; Carpinella, M.; Albert, G.; Osán, T. M.; Olle, J. M.; Freeman, J.; Appel, M. y Espejo, I. "Magnetic resonance based apparatus and method to analyze and to measure the bi-directional *flow regime in a transport or a production conduit of complex fluids, in real time and real flow-rate"*. Patente otorgada (2011), Shell Oil Company (Houston, TX): United States Patent. 7,872,474

- Pusiol, D. J.; Osán T.M.; Carpinella M. "*Cylindrical Gradient Coil Set for NMR and MRI Magnets with Transverse Magnetic Field", (Provisional)*. Mayo 2010, Spinlock s.r.l.: United state Patent. Número de aplicación 61332800.

c. Publicaciones en congresos

- Mariela Carpinella, Tristán M. Osán, Lucas M. C. Cerioni, Mariano Medina, Daniel J.Pusiol, Matthias Appel, Justin Freeman and Irene Espejo. *"Flow Regime Analyzer Based On Low-Field Magnetic Resonance And Halbach Type Magnet Arrangements"*. Euromar 2010 y 17th ISMAR Conference. Florencia. Italia, Julio 2010.

- Mariela Carpinella, Tristán M. Osán, Lucas M. C. Cerioni, Mariano Medina, Daniel J.Pusiol, Matthias Appel, Justin Freeman and Irene Espejo. *"Flow Regime Analyzer Based on Low-Field Nuclear Magnetic Resonance and Halbach Type Magnets"*. Magnetic Resonance in a Cordubensis Perspective: New developments in NMR. Septiembre 2011. Alta Gracia, Córdoba, Argentina.

Bibliografía

1. Falcone, G., G.F. Hewitt, and C. Alimonti, *MULTIPHASE FLOW METERING*. 2009, Oxford: Elsevier.
2. Hall, A.R.W., *MULTIPHASE FLOW OF OIL, WATER AND GAS IN HORIZONTAL PIPES*, in *Imperial College of Science, Technology and Medicine,*. 1992, University of London: London. p. 300.
3. Khor, S.H., *Three-Phase Liquid-Liquid-Gas Stratified Flow In Pipelines* in *Chemical Engineering and Chemical Technology*. 1998, Imperial College of Science, Technology and Medicine: London
4. Thorn, R., G.A. Johansen, and E.A. Hammer, *Recent developments in three-phase flow measurements.* Measurement Science and Technology, 2004. **8**(7).
5. GLADDEN, L.F., et al., *Dynamic MR Imaging of Single and Two-Phase Flows.* Chemical Engineering Research and Design, 2006. **84**: p. 272–281.
6. Caprihan, A. and E. Fukushima, *Flow measurements by NMR.* Physics Reports, 1990. **198**(4): p. 195-235.
7. Hills, B.P. and K.M. Wright, *Motional relativity and industrial NMR sensors.* Journal of Magnetic Resonance, 2006. **178**(2): p. 193-205.
8. Pusiol, D., et al., *Magnetic resonance based apparatus and method to analyze and to measure the bi-directional flow regime in a transport or a production conduit of complex fluids, in real time and real flow-rate*. 2011, Shell Oil Company (Houston, TX): United States Patent.
9. Osán, T.M., et al., *Fast measurements of average flow velocity by Low-Field 1H NMR.* Journal of Magnetic Resonance, 2011. **209**(2): p. 116-122.
10. Pusiol, D.J., O. T.M., and C. M., *Cylindrical Gradient Coil Set for NMR and MRI Magnets with Transverse Magnetic Field, (Provisional)*. 2010, Spinlock s.r.l.: United state Patent
11. Keeler, J., *Understanding NMR Spectroscopy*. 2005: Wiley.
12. Callaghan, P.T., *Principles of nuclear magnetic resonance microscopy*. 1991: Oxford University Press.
13. Hahn, E.L., *Spin Echoes.* Physical Review, 1950. **80**(4): p. 580-594.
14. Carr, H.Y. and E.M. Purcell, *Effects of Diffusion on Free Precession in Nuclear Magnetic Resonance Experiments.* Physical Review, 1954. **94**(3): p. 630-638.
15. Meiboom, S. and D. Gill, *Modified Spin-Echo Method for Measuring Nuclear Relaxation Times.* Review of Scientific Instruments, 1958. **29**(8): p. 688-691.
16. Slichter, C.P., *Principles of Magnetic Resonance*. 1990, Heidelberg, Germany: Springer Verlag.
17. Price, W.S., *Pulsed-field gradient nuclear magnetic resonance as a tool for studying translational diffusion: Part 1. Basic theory.* Concepts in Magnetic Resonance, 1997. **9**(5): p. 299-336.
18. Batchelor, J.K., *An Introduction to Fluid Dynamics*. 1967, Cambridge: Cambridge Univerity Press.
19. Suryan, G., *Nuclear resonance in flowing liquids.* Proc. Indian Acad. Sci. Sect. A, 1951. **33** p. 107–111.
20. Singer, J.R., *Blood Flow Rates by Nuclear Magnetic Resonance Measurements.* Science, 1959. **130**(3389): p. 1652-1653.
21. Hirschel, L.R. and L.F. Libelo, *Nuclear Magnetic Resonance in Flowing Fluids.* Journal of Applied Physics, 1961. **32**(7): p. 1404-1405.

22. Hirschel, L.R. and L.F. Libelo, *NMR Signal Dependence on Fluid Velocity.* Journal of Applied Physics, 1962. **33**(5): p. 1895-1896.
23. Arnold, D.W. and L.E. Burkhart, *Spin-Echo NMR Response from a Flowing Sample.* Journal of Applied Physics, 1965. **36**(3): p. 870-871.
24. Stejskal, E.O., *Use of Spin Echoes in a Pulsed Magnetic-Field Gradient to Study Anisotropic, Restricted Diffusion and Flow.* The Journal of Chemical Physics, 1965. **43**(10): p. 3597-3603.
25. Grover, T. and J.R. Singer, *NMR Spin-Echo Flow Measurements.* Journal of Applied Physics, 1971. **42**(3): p. 938-940.
26. Packer, K.J., *The study of slow coherent molecular motion by pulsed nuclear magnetic resonance.* Molecular Physics, 1969. **17**: p. 355–368.
27. Hayward, R.J., K.J. Packer, and D.J. Tomlinson, *Pulsed field-gradient spin echo NMR studies of flow in fluids.* Molecular Physics, 1972. **23** p. 1083–1102.
28. Hemminga, M.A., P.A. de Jager, and A. Sonneveld, *The study of flow by pulsed nuclear magnetic resonance. I. Measurement of flow rates in the presence of a stationary phase using a difference method.* Journal of Magnetic Resonance (1969), 1977. **27**(3): p. 359-370.
29. Gladden, L.F. and P. Alexander, *Applications of nuclear magnetic resonance imaging in process engineering.* Measurement Science and Technology, 1996. **7**(3): p. 423-435.
30. Fukushima, E., *Nuclear Magnetic Resonance as a Tool to Study Flow.* Annual Review of Fluid Mechanics, 1999. **31**(1): p. 95-123.
31. Stejskal, E.O. and J.E. Tanner, *Spin Diffusion Measurements: Spin Echoes in the Presence of a Time-Dependent Field Gradient.* The Journal of Chemical Physics, 1965. **42**(1): p. 288-292.
32. Jones, D.W. and T.F. Child, *NMR in flowing systems*, in *Advances in Magnetic Resonance*, J.S. Waugh, Editor. 1976, Academic Press. p. 123–148.
33. Keifer, P.A., *Flow techniques in NMR spectroscopy.* Annual Review in NMR Spectroscopy. , 2007. **62** p. 2– 40.
34. Manz, B., *Combined relaxation and displacement experiment: a fast method to acquire T2, diffusion and velocity maps.* Journal of Magnetic Resonance, 2004. **169**(1): p. 60-67.
35. Pope, J.M. and S. Yao, *Quantitative NMR imaging of flow.* Concepts in Magnetic Resonance, 1993. **5**(4): p. 281-302.
36. Stepišnik, J., *Measuring and imaging of flow by NMR.* Progress in Nuclear Magnetic Resonance Spectroscopy, 1985. **17**(0): p. 187-209.
37. Han, S.-I., et al., *Rheology of Blood by NMR.* Journal of Magnetic Resonance, 2001. **152**(1): p. 87-94.
38. Bagueira de Vasconcellos Azeredo, R.B.d.V., M. Engelsberg, and L.A. Colnago, *Flow sensitivity and coherence in steady-state free spin precession.* Physical Review E, 2001. **64**(1): p. 016309.
39. Song, Y.-Q. and U.M. Scheven, *An NMR technique for rapid measurement of flow.* Journal of Magnetic Resonance, 2005. **172**(1): p. 31-35.
40. Galvosas, P. and P.T. Callaghan, *Fast magnetic resonance imaging and velocimetry for liquids under high flow rates.* Journal of Magnetic Resonance, 2006. **181**(1): p. 119-125.
41. Li, T.-Q., et al., *Turbulent pipe flow studied by time-averaged NMR imaging: Measurements of velocity profile and turbulent intensity.* Magnetic Resonance Imaging, 1994. **12**(6): p. 923-934.

42. Song, Y.Q., *Categories of Coherence Pathways for the CPMG Sequence.* Journal of Magnetic Resonance, 2002. **157**(1): p. 82-91.
43. Hürlimann, M.D., *Diffusion and Relaxation Effects in General Stray Field NMR Experiments.* Journal of Magnetic Resonance, 2001. **148**(2): p. 367-378.
44. Amar, A., B. Blümich, and F. Casanova, *Rapid Multiphase Flow Dynamics Mapped by Single-Shot MRI Velocimetry.* ChemPhysChem, 2010. **11**(12): p. 2630-2638.
45. Kuethe, D.O., *Measuring distributions of diffusivity in turbulent fluids with magnetic-resonance imaging.* Physical Review A, 1989. **40**(8): p. 4542-4551.
46. Kose, K., *Instantaneous flow-distribution measurements of the equilibrium turbulent region in a circular pipe using ultrafast NMR imaging.* Physical Review A, 1991. **44**(4): p. 2495-2504.
47. Sederman, A.J., et al., *MRI technique for measurement of velocity vectors, acceleration, and autocorrelation functions in turbulent flow.* Journal of Magnetic Resonance, 2004. **166**(2): p. 182-189.
48. Blümich, B., *NMR Imaging of Materials*. 2000, Oxford: Clarendon Press.
49. Casanova, F., J. Perlo, and B. Blümich, *Velocity distributions remotely measured with a single-sided NMR sensor.* Journal of Magnetic Resonance, 2004. **171**(1): p. 124-130.
50. Perlo, J., F. Casanova, and B. Blümich, *Velocity imaging by ex situ NMR.* Journal of Magnetic Resonance, 2005. **173**(2): p. 254-258.
51. Hürlimann, M.D. and D.D. Griffin, *Spin Dynamics of Carr–Purcell–Meiboom–Gill-like Sequences in Grossly Inhomogeneous B0 and B1 Fields and Application to NMR Well Logging.* Journal of Magnetic Resonance, 2000. **143**(1): p. 120-135.
52. Ahola, S., et al., *Multiecho sequence for velocity imaging in inhomogeneous rf fields.* Journal of Magnetic Resonance, 2006. **182**(1): p. 143-151.
53. Krüger, G.J., A. Birke, and R. Weiss, *Nuclear magnetic resonance (NMR) two-phase mass flow measurements.* Flow Measurement and Instrumentation, 1996. **7**(1): p. 25-37.
54. Lynch, G.F. and S.L. Segel, *Direct measurement of the void fraction of a two-phase fluid by nuclear magnetic resonance.* International Journal of Heat and Mass Transfer, 1977. **20**(1): p. 7-14.
55. Abouelwafa, M.S.A. and E.J.M. Kendall, *Optimization of continuous wave nuclear magnetic resonance to determine in situ volume fractions and individual flow rates in two component mixtures.* Review of Scientific Instruments, 1979. **50**(12): p. 1545-1549.
56. Daidzic, N.E., et al., *Gas–liquid phase distribution and void fraction measurements using MRI.* Nuclear Engineering and Design, 2005. **235**(10–12): p. 1163-1178.
57. Leblond, J., et al., *Two-phase flow characterization by nuclear magnetic resonance.* Nuclear Engineering and Design, 1998. **184**(2–3): p. 229-237.
58. Majors, P.D., R.C. Givler, and E. Fukushima, *Velocity and concentration measurements in multiphase flows by NMR.* Journal of Magnetic Resonance (1969), 1989. **85**(2): p. 235-243.
59. Blümich, B., et al., *Mobile NMR for porosity analysis of drill core sections.* J. Geophys. Eng., 2004 **1**: p. 177–180.
60. Hickey, H., et al., *Magnetic resonance relaxation measurements to determine oil and water content in fried foods.* Food Research International 2006. **39**: p. 612–618.
61. Casanova, F., et al., *Multi-echo imaging in highly inhomogeneous magnetic fields.* Journal of Magnetic Resonance, 2004. **166**(1): p. 76-81.
62. Kimmich, R., *NMR Tomography, Diffusometry, Relaxometry*. 1997, Berlin Heidelberg Springer Verlag

63. Haacke, E.M., et al., *Magnetic Resonance Imaging: Physical Principles and Sequence Design* 1999: Wiley and Sons.
64. Perlo, J., F. Casanova, and B. Blümich, *3D imaging with a single-sided sensor: an open tomograph.* Journal of Magnetic Resonance, 2004. **166**(2): p. 228-235.
65. Campbell, P., *Permanent magnet materials and their application*. 1994, Cambridge: Cambridge University Press.
66. Mauler, J., et al., *Identification of liquids encountered in carry – on- luggage by mobile NMR.* Explosive detection using magnetic and nuclear Resonance Techniques, 2009.
67. Guthausen, A., et al., *Measurement of fat content of food with single-sided NMR.* Journal of the American Oil Chemists' Society, 2004. **81**(8): p. 727-731.
68. Milczarek, R.R. and M.J. McCarthy, *Low - Field MR Sensors for Fruit Inspection*, in *Magnetic Resonance Microscopy: Spatially Resolved NMR Techniques and Applications*, C. S. and S.J. D., Editors. 2009, Wiley-VCH.
69. Rahmatallah, S., et al., *Measurement of relaxation times in foodstuffs using a one-sided portable magnetic resonance probe.* European Food Research and Technology, 2006. **222**(3): p. 298-301.
70. Todt, H., et al., *Water/moisture and fat analysis by time-domain NMR.* Food Chemistry, 2006. **96**(3): p. 436-440.
71. Hills, B.P., *Applications of Low-Field NMR to Food Science*, in *Annual Reports on NMR Spectroscopy*, G.A. Webb, Editor. 2006, Academic Press. p. 177-230.
72. Windt, C.W., et al., *A portable Halbach magnet that can be opened and closed without force: The NMR-CUFF.* Journal of Magnetic Resonance, 2011. **208**(1): p. 27-33.
73. Casanova, F., J. Perlo, and B. Blümich, eds. *Single Sided NMR*. 2011, Springer-Verlag: Berlin.
74. Freedman, R. and C. Morriss, *Processing data from an NMR logging tool.*, in *70th SPE Annual Technical Conference and Exhibition*. 1995: Dallas, TX.
75. Kenyon, W., et al., *Pore size distribution and NMR in microporous cherty sandstones*, in *Transactions of the SPWLA 30th Annual Logging Symposium*. 1989: Denver.
76. Kleinberg, R.L., et al., *Novel NMR apparatus for investigating an external sample.* Journal of Magnetic Resonance (1969), 1992. **97**(3): p. 466-485.
77. Murphy, D., *Advances in MWD and formation evaluation for 1995.* World Oil 1995. **216**: p. 39–49.
78. Woessner, D.E., *The early days of NMR in the Southwest.* Concepts in Magnetic Resonance, 2001. **13**(2): p. 77-102.
79. Anferov, V., et al., *Mobile NMR scanners for nondestructive measurements of porosity of drill cores.* Magnetic Resonance Imaging, 2007. **25**(4): p. 547.
80. Anferova, S., et al., *Improved Halbach sensor for NMR scanning of drill cores.* Magnetic Resonance Imaging, 2007. **25**(4): p. 474-480.
81. Anferova, S., et al., *A mobile NMR device for measurements of porosity and pore size distributions of drilled core samples.* Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering, 2004. **23B**(1): p. 26-32.
82. Anferova, S., et al., *Determination of porosity and novel 2D relaxation and diffusion experiments with mobile NMR halbach scanner.* Magnetic Resonance Imaging, 2007. **25**(4): p. 547-548.
83. Danieli, E., et al., *Small Magnets for Portable NMR Spectrometers.* Angewandte Chemie International Edition, 2010. **49**(24): p. 4133-4135.

84. Marko, A., B. Wolter, and W. Arnold, *Application of a portable nuclear magnetic resonance surface probe to porous media.* Journal of Magnetic Resonance, 2007. **185**(1): p. 19-27.
85. Neudert, O., S. Stapf, and C. Mattea, *Diffusion exchange NMR spectroscopy in inhomogeneous magnetic fields.* Journal of Magnetic Resonance, 2011. **208**(2): p. 256-261.
86. Blümich, B., J. Perlo, and F. Casanova, *Mobile single-sided NMR.* Progress in Nuclear Magnetic Resonance Spectroscopy, 2008. **52**(4): p. 197-269.
87. Hürlimann, M.D., *Ex Situ Measurement of One- and Two-Dimensional Distribution Functions*, in *Single-Sided NMR*, F. Casanova, J. Perlo, and B. Blümich, Editors. 2011, Springer-Verlag: Berlin Heidelberg p. 57.
88. Blümich, B., et al., *Degradation of historical paper: nondestructive analysis by the NMR-MOUSE.* Journal of Magnetic Resonance, 2003. **161**(2): p. 204-209.
89. Blümich, B., et al., *Small-scale instrumentation for nuclear magnetic resonance of porous media.* New Journal of Physics 2011. **13**
90. Blümich, B., et al., *Advances of unilateral mobile NMR in nondestructive materials testing.* Magnetic Resonance Imaging, 2005. **23**(2): p. 197-201.
91. Blümich, B., et al., *Mobile NMR for geophysical analysis and materials testing.* Petroleum Science, 2009. **6**(1): p. 1-7.
92. Guthausen, A., et al., *Analysis of Polymer Materials by Surface NMR via the MOUSE.* Journal of Magnetic Resonance, 1998. **130**(1): p. 1-7.
93. Marble, A.E., et al., *A constant gradient unilateral magnet for near-surface MRI profiling.* Journal of Magnetic Resonance, 2006. **183**(2): p. 228-234.
94. Poli, T., et al., *A portable NMR device for the evaluation of water presence in building materials.* Journal of Cultural Heritage, 2007. **8**(2): p. 134-140.
95. Prado, P.J., B. Blümich, and U. Schmitz, *One-Dimensional Imaging with a Palm-Size Probe.* Journal of Magnetic Resonance, 2000. **144**(2): p. 200-206.
96. Perlo, J., F. Casanova, and B. Blümich, *Ex Situ NMR in Highly Homogeneous Fields: 1H Spectroscopy.* Science, 2007. **315**(5815): p. 1110-1112.
97. Haken, R. and B. Blümich, *Anisotropy in Tendon Investigated in Vivo by a Portable NMR Scanner, the NMR-MOUSE.* Journal of Magnetic Resonance, 2000. **144**(2): p. 195-199.
98. Leupold, H.A. and I.E. Potenziani, *Permanent magnet structure for a nuclear magnetic resonance imager for medical diagnostics* 1990, The United States of Americas as represented by the Secretary of the Army USA.
99. Jackson, J.A., L.J. Burnett, and J.F. Harmon, *Remote (inside-out) NMR. III. Detection of nuclear magnetic resonance in a remotely produced region of homogeneous magnetic field.* Journal of Magnetic Resonance (1969), 1980. **41**(3): p. 411-421.
100. Burnettt, L.J. and J.A. Jackson, *Remote (inside-out) NMR. II. Sensitivity of NMR detection for external samples.* Journal of Magnetic Resonance (1969), 1980. **41**(3): p. 406-410.
101. Cooper, R.K. and J.A. Jackson, *Remote (inside-out) NMR. I. Remote production of region of homogeneous magnetic field.* Journal of Magnetic Resonance (1969), 1980. **41**(3): p. 400-405.
102. Hogan, B.J., *One-sided NMR sensor system measures soil/concrete moisture.* Design News, 1985.
103. Blümich, B., et al., *The NMR-mouse: construction, excitation, and applications.* Magnetic Resonance Imaging, 1998. **16**(5–6): p. 479-484.
104. Casanova, F. and B. Blümich, *Two-dimensional imaging with a single-sided NMR probe.* Journal of Magnetic Resonance, 2003. **163**(1): p. 38-45.

105. Eidmann, G., et al., *The NMR MOUSE, a Mobile Universal Surface Explorer.* Journal of Magnetic Resonance, Series A, 1996. **122**(1): p. 104-109.
106. Blümich, B., et al., *Simple NMR-mouse with a bar magnet.* Concepts in Magnetic Resonance, 2002. **15**(4): p. 255-261.
107. Rahmatallah, S., et al., *NMR detection and one-dimensional imaging using the inhomogeneous magnetic field of a portable single-sided magnet.* Journal of Magnetic Resonance, 2005. **173**(1): p. 23-28.
108. Manz, B., et al., *A mobile one-sided NMR sensor with a homogeneous magnetic field: The NMR-MOLE.* Journal of Magnetic Resonance, 2006. **183**(1): p. 25-31.
109. Demas, V. and P.J. Prado, *Compact magnets for magnetic resonance.* Concepts in Magnetic Resonance Part A, 2009. **34A**(1): p. 48-59.
110. Halbach, K., *Design of permanent multipole magnets with oriented rare-earth cobalt material.* Nuclear Instruments & Methods, 1980. **169** p. 1–10.
111. jackson, J.D., *Electrodinamica Clasica*. Vol. 2a ed. 1980, Madrid: Alhambra Longman.
112. Zhu, Z.Q. and D. Howe, *Halbach permanent magnet machines and applications: a review.* IEE proc. Electr. Appl. , 2001. **148**(4).
113. Leupold, H.A., A.S. Tilak, and E. Potenziani Ii, *Multi-Tesla permanent magnet field sources.* Journal of Applied Physics, 1993. **73**(10): p. 6861-6863.
114. Moresi, G. and R. Magin, *Miniature permanent magnet for table-top NMR.* Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering, 2003. **19B**(1): p. 35-43.
115. Raich, H. and P. Blümler, *Design and Construction of a Dipolar Halbach Array with a Homogeneous Field from Identical Bar Magnets: NMR Mandhalas.* Concepts in Magnetic Resonance, 2004. **23B** (1): p. 16 -25
116. Zhu, Z.Q., et al. *Novel permanent Magnet Machines Using Halbach Cylinders*. in *Power Electronics and Motion Control Conference, Proceedings. IPEMC*. 2000. Beijing , China.
117. Beer, S., *Permanent magnet ring assembly for NMR imaging system and method for using such assembly* 1987, Elscint Ltd. (Haifa, IL) United States Patent
118. Arnold, J., *Mobile NMR for rock porosity and permeability.*, in *Recursos geológicos e Ingeniería de Materiales* 2007, Universidad RWTH Aachen: Düsseldorf
119. Danieli, E., et al., *Mobile sensor for high resolution NMR spectroscopy and imaging.* Journal of Magnetic Resonance, 2009. **198**(1): p. 80-87.
120. Hills, B.P., K.M. Wright, and D.G. Gillies, *A low-field, low-cost Halbach magnet array for open-access NMR.* Journal of Magnetic Resonance, 2005. **175**(2): p. 336-339.
121. Chang, W.-H., J.-H. Chen, and L.-P. Hwang, *Single-sided mobile NMR with a Halbach magnet.* Magnetic Resonance Imaging, 2006. **24**(8): p. 1095-1102.
122. Aubert, G., *Cylindrical permanent magnet with longitudinal induced field*. 1991, Centre National de la Recherche Scientifique: United States Patent
123. Hugon, C., et al., *Design, fabrication and evaluation of a low-cost homogeneous portable permanent magnet for NMR and MRI.* Comptes Rendus Chimie, 2010. **13**(4): p. 388-393.
124. Hugon, C., et al., *Design of arbitrarily homogeneous permanent magnet systems for NMR and MRI: Theory and experimental developments of a simple portable magnet.* Journal of Magnetic Resonance, 2010. **205**(1): p. 75-85.
125. Chmurny, G.N. and D.I. Hoult, *The Ancient and Honourable Art of Shimming.* Concepts in Magnetic Resonance, 1990. **2**(3): p. 131-149.

126. GOLAY, M.J.E., *Field Homogenizing Coils for Nuclear Spin Resonance Instrumentation.* THE REVIEW OF SCIENTIFIC INSTRUMENTS, 1958. **29**: p. 3l3-315.
127. Dorri, B., M.E. Vermilyea, and W.E. Toffolo, *Passive Shimming of MR Magnets: Algorithm, Hardware, and Results.* IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, 1993. **3**(1): p. 254-257.
128. Bertora, F., et al., *Shimming of yokeless permanent magnets designed to generate uniform fields.* Journal of Applied Physics, 1993. **73**(10): p. 6864-6866.
129. Zhao, W., et al., *Passive Shimming for a Permanent MRI Magnet.* Journal of Iron and Steel Research, International, 2006. **13, Supplement 1**(0): p. 415-418.
130. Danieli, E.P., et al., *High-performance shimming with permanent magnets*, in *Magnetic Resonance Microscopy: Spatially Resolved NMR Techniques and Applications*, C. S. and S.J. D., Editors. 2009, WILEY-VCH Weinheim. p. 487–499.
131. Jachmann, R.C., et al., *Multipole shimming of permanent magnets using harmonic corrector rings.* Review of Scientific Instruments 2007. **78**
132. Leupold, H.A. and E. Potenziani Ii, *Augmentation of field uniformity and strength in spherical and cylindrical magnetic field sources.* Journal of Applied Physics, 1991. **70**(10): p. 6621-6623.
133. Cullity, B.D. and C.D. Graham, *Introduction to Magnetic Materials*. 2nd Edition ed. 2008, Hoboken, New Jersey: Wiley-IEEE Press.
134. Ningbo Ninggang, P.M., *Demagnetization curves, http://www.ngyc.com/wendu.html*. 2011.
135. Prammer, M.G. and P. Masak, *Temperature Compensated Magnetic Field Apparatus for NMR Measurements*. 2003, Halliburton Energy Services, Inc.: United States Patent
136. IATA, *Dangerous Goods Regulations, http://www.iata.org/whatwedo/cargo/dangerous_goods/Pages/index.aspx*
137. Magnet Sales Manufacturing, i., *Table of Properties for SmCo Magnets*. 2011, Total Magnetic Solutions, http://www.magnetsales.com/SMCO/smcoprops.htm.
138. Ningbo Ninggang, P.M., *Sintered SmCo magnet, Physical Properties, http://www.ngyc.com/xingneng.html*. 2011.
139. Liu, J.F. and M.H. Walmer, *Thermal Stability and Performance Data for SmCo 2:17 High-Temperature Magnets on PPM Focusing Structures.* IEEE TRANSACTIONS ON ELECTRON DEVICES, 2005. **52**(5).
140. Arnold, M.T., *Using Permanent Magnets at Low Temperatures, TECHNotes. http://spontaneousmaterials.com/Papers/TN_0302.pdf*. 2003.
141. Jin, J., *Electromagnetic Analysis and Design in Magnetic Resonance Imaging*. 1998 Urbana-Champaign, Illinois, USA: CRC Press.
142. Suhu, S.C. and A. Majumdar, *Pulsed-Field gradient-based water suppression techniques in homonuclear NMR spectroscopy.* Current Science, 1998. **74**(5).
143. Petropoulos, L.S., *Single gradient coil configuration for MRI systems with orthogonal directed magnetic fields* 1999, Picker International, Inc. : United States Patent
144. Moon, C.H., et al., *Design of Convex – Surface Gradient Coils for a Vertical – Field Open MRI System.* Measurement Science and Technology, 2000. **11**: p. N89-N94.
145. Ohliger, M.A. and D.K. Sodickson, *An introduction to coil array design for parallel MRI.* NMR in Biomedicine, 2006. **19**(3): p. 300-315.
146. Anferova, S., et al., *Construction of a NMR-MOUSE with short dead time.* Concepts in Magnetic Resonance, 2002. **15**(1): p. 15-25.
147. Gerothanassis, I.P., *Methods of avoiding the effects of acoustic ringing in pulsed fourier transform nuclear magnetic resonance spectroscopy.* Progress in Nuclear Magnetic Resonance Spectroscopy, 1987. **19**(3): p. 267-329.

148. Bowtell, R. and P. Mansfield, *Screened Coil Design for NMR Imaging in Magnets with Transverse Field Geometry*. Measurement Science and Technology, 1990. **1**: p. 431-439.

149. Separovic, F., B. Cornell, and R. Pace, *Orientation dependence of NMR relaxation time, T1ρ, in lipid bilayers.* Chemistry and Physics of Lipids, 2000. **107**(2): p. 159-167.

150. Ernst, R.R., G. Bodenhausen, and A. Wokaun, *Principles of Nuclear Magnetic Resonance in One and Two Dimensions*. 1990, USA: Oxford University Press.