

# Magnetic Hyperthermia for Particle Image Velocimetry (MH-PIV)

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In this work a novel approach is investigated for Particle Image Velocimetry (PIV) which is a technique used as optical method for instantaneous flow visualization. So far traditional PIV is based in the injection of small seed-particles which are entrained by the flow and illuminated so that particles are visible and the motion of the seeding particles is used to calculate speed and direction of the flow. Here, the seed-particles are replaced by magnetic clusters and instead to be illuminated are subjected to alternating magnetic field which result in local hyperthermia of the cluster owing to the dissipative power from the motion in the viscous medium. The heat radiation emitted by the particles may be detected by infrared cameras which impressive achievement in the last decade permit to analyze dynamic events. Because the most recent advances in detection and tracking in thermal infrared imagery, Thermal-PIV by the use of hyperthermal magnetic clusters allow a unique feature, namely, the visualization of flows through opaque bodies which, could have important applications not only in the industry but in medicine. Utilizing a physical model the heating dissipative power was studied and computational fluid dynamics (CFD) simulations were performed.

**Keywords.** *Magnetic particles; Heating; Particle Image Velocimetry*

## I. INTRODUCTION

Despite that the activation of colloidal magnetic fluids (magnetic nanoparticles) by an alternating magnetic field with application to medical treatments (hyperthermia therapy) has been investigated since the final decade of the last century, [1], however, today is still an active important area of research and new methods, materials and optimization procedures are being investigated, [2]-[6].

In other research field, detection and tracking in thermal infrared imagery has experienced an extraordinary evolution in the last years, and today powerful detectors with high sensibility and competitive cost are available for research and industry. This evolution in image quality and resolution combined with decreasing price and size have opened up new application areas,[7], and for example, FAST-IR infrared cameras which allow high-speed thermal imaging with an impressive temporal resolution at a rapid frame rate. These high- performance infrared cameras are extremely sensitive enabling the detection of challenging targets and dynamic events.

On the other hand, particle image velocimetry (PIV) is a technique used as optical method for instantaneous flow visualization. So far traditional PIV is based in the injection of small seed-particles which are entrained by the flow and illuminated so that particles are visible and the motion of the seeding particles is used to calculate

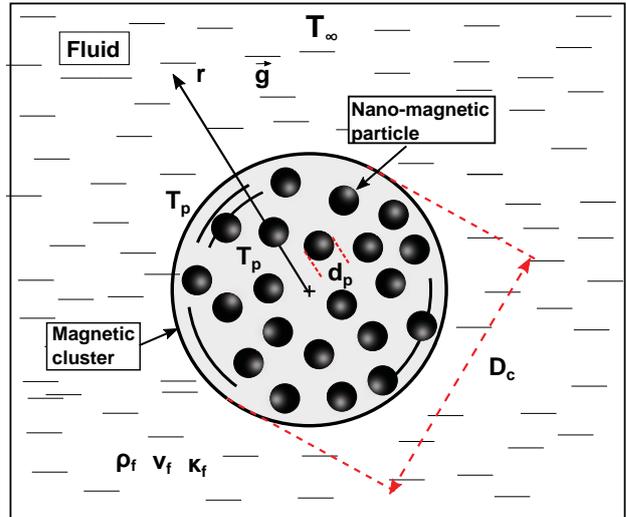


FIG. 1. Physical model of the magnetic cluster immersed into a fluid and heated by an alternating magnetic field

speed and direction of the flow.

By aforementioned, a natural question arises, namely, it could be possible to use magnetic hyperthermia for particle image velocimetry (PIV) using detection and tracking with thermal infrared sensors?. The object of this work was a first assessment on this new application for magnetic hyperthermia.

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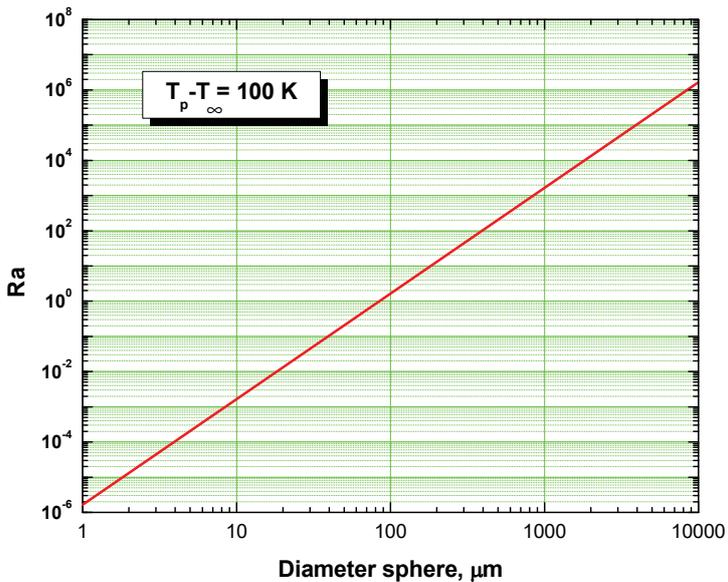


FIG. 2. Rayleigh number  $\mathbf{Ra}$  as a function of the diameter of the sphere.

## II. MATERIALS AND METHODS

To begin with, for PIV it is desired that the particles be small enough so that response time of the particles to the motion of the fluid is reasonably short to accurately follow the flow (low Stokes number and then perfect advection) and then PIV seed-particles are typically of a diameter in the order of 10 to 100 micrometers. Therefore, instead to talk of magnetic particles, it is more proper to talk on magnetic clusters grouping thousands of nanoparticles in a fashion more or less as depicted in Fig.1.

Now we can proceed to calculate the power dissipation when the cluster is subject to alternating magnetic field.

First, in steady state from a balance of energy we have

$$h_t(T_p - T_\infty)S_c = P_p \cdot V_c \quad (1)$$

where  $h_t$  is the total heat transfer (including conduction and convection);  $T_p$  is the temperature of the cluster which because its small dimensions can be assumed as the same temperature than the nanoparticles inside;  $T_\infty$  the quiescent temperature (fluid temperature far from the surface of the particle);  $S_c$  and  $V_c$  are the surface and the volume of the cluster, respectively;  $P_p$  is the volumetric power dissipation.

The total heat transfer coefficient can be related with the Nusselt number by

$$\mathbf{Nu} = \frac{h_c + h_\kappa}{h_\kappa} \quad (2)$$

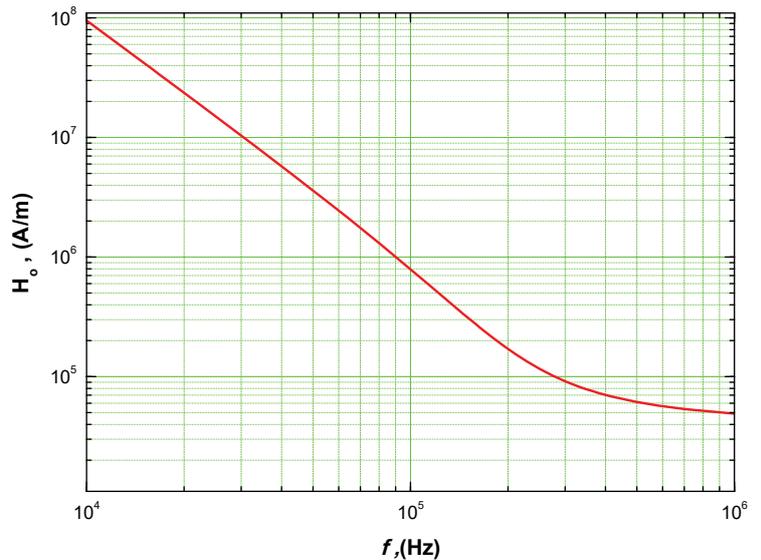


FIG. 3. Magnetic field as function of frequency to rise the cluster at 50 K

where  $h_c$  and  $h_\kappa$  are the convective and conductive heat transfer coefficients.

Several semiempirical expressions are available for the Nusselt number, however almost all of them follow a power-law, [8]

$$\mathbf{Nu} = c_1 \mathbf{Ra}^m \quad (3)$$

where  $0 < c < 1$  is a constant;  $\mathbf{Ra}$  the Rayleigh number; and  $m$  is an index. The index is always between  $\frac{1}{4}$  to  $\frac{1}{3}$ . Therefore, we can infer that convective heat transfer becomes more important than conduction for  $\mathbf{Ra} > 10^4$  if  $m = \frac{1}{4}$ ; or  $\mathbf{Ra} > 10^3$  if  $m = \frac{1}{3}$  is considered. Fig. 2 shows the Rayleigh number as function of the radius of the sphere considering a difference of temperatures between the surface of the sphere  $T_p$  and the quiescent temperature  $T_\infty$  equal to 100 K and considering water as fluid. It is seen that for small clusters as desired in PIV (10-to-100 $\mu$  m) the Rayleigh number is clearly small than unity and then convection is unimportant in comparison with conduction.

Thus, taking into account thermal conduction as the dominant mechanism, and considering that conductive heat transfer coefficient for a sphere surrounding by an infinite medium is given by,[12]

$$h_\kappa = \frac{2\kappa_f}{D_c} \quad (4)$$

where  $\kappa_f$  is the thermal conductivity of the fluid;  $D_c$  the diameter of the spherical cluster. Taking into account that for a spherical cluster  $S_c = \pi D_c^2$  and  $V_c = \frac{\pi D_c^3}{6}$  and with  $h_t = h_\kappa$  and using Eq.(4), Eq.(1) becomes

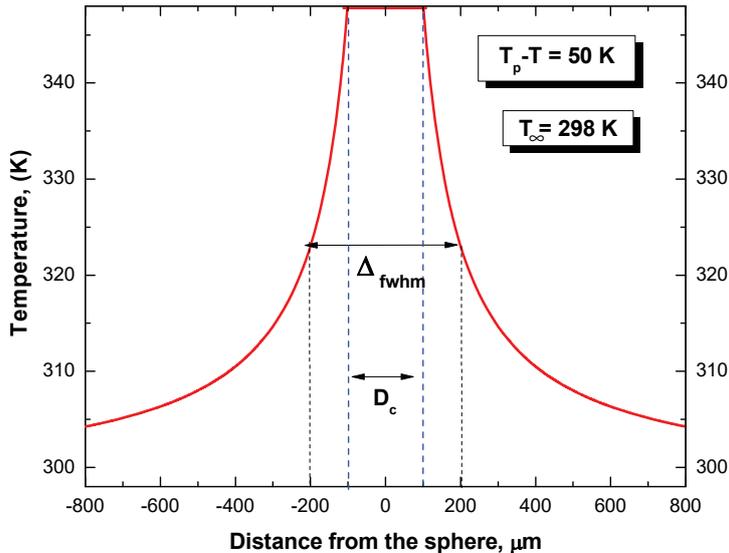


FIG. 4. FWHM  $\Delta_{fwhm}$  for a sphere with a diameter  $D_c = 100\mu\text{ m}$   $T_\infty = 298\text{ K}$  and a cluster temperature  $T_p = 348\text{ K}$

$$P_p = \frac{12\kappa_f(T_p - T_\infty)}{D_c^2} \quad (5)$$

Finally we need some expression for the dissipative power per unit of volume of the magnetic particle under an alternating magnetic field. As first approximation we can consider a system formed by monoparticles with the same size. This power was calculated by Rosensweig (2002) and is given by the following relationship, [9]

$$P_m = \frac{\mu_o H_o M_s \omega^2 \tau}{2} \left[ \frac{1}{1 + (\omega\tau)^2} \right] \left[ \coth \xi - \frac{1}{\xi} \right] \quad (6)$$

where  $\mu_o = 4\pi \times 10^{-7}(\text{TmA}^{-1})$  is the permeability of free space;  $H_o$  the amplitude of the magnetic field applied;  $M_s$  is saturation magnetization;  $\omega$  the cyclic frequency of the alternating magnetic field  $H$ ; i.e.,  $H = H_o \cos \omega t$  being  $t$  the time;  $\tau$  is the Brownian time constant given by

$$\tau = \frac{\pi \rho_f \nu_f d_p^3}{2\kappa_B T_p} \quad (7)$$

where  $d_p$  is the diameter of the nanoparticle;  $\kappa_B = 1.38 \times 10^{-23} \text{ JK}^{-1}$  is the Boltzmann constant; and

$$\xi = \frac{\pi \mu_o M_s H_o d_p^3}{6\phi \kappa_B T_p} \quad (8)$$

where  $\phi$  is the volume fraction of solids. Equating Eq.(6) with Eq.(5) yields

$$\left[ \frac{H_o \omega^2}{T_p - T_\infty} \right] \left[ \frac{1}{1 + (\omega\tau)^2} \right] \left[ \coth \xi - \frac{1}{\xi} \right] = \frac{24\kappa_f}{\mu_o M_s \tau D_c^2} \quad (9)$$

### • Discussion

Eq.(9) allow us to fix the desired temperature of the cluster  $T_p$  by fixing the amplitude of the magnetic field  $H_o$  and its frequency  $\omega$ . In order to obtain some idea we assume some typical values of the parameters using water as the fluid transporting the cluster:  $T_p = 350\text{ K}$ ;  $T_\infty = 298\text{ K}$ ;  $\kappa_f = 0.5\text{ W/(mK)}$ ;  $M_s = 4 \times 10^5\text{ A/m}$ ;  $D_c = 10^{-4}\text{ m}$ ;  $d_p = 10^{-8}\text{ m}$ ;  $\rho_f = 10^3\text{ kg/m}^3$ ;  $\nu_f = 10^{-6}\text{ m}^2/\text{s}$ ;  $\phi = 0.06$ . The resulting curve is shown in Fig. 3. It is seen that from frequencies around 300 kHz it will required amplitudes around  $10^5\text{ A/m}$  which is in the order of magnitude of a typical hand-held permanent magnet.

### III. TEMPERATURE PROFILE

As previously discussed, the heat transfer from the surface of the microscopic cluster is due to conduction, and thus, the radial temperature profile surrounding the spherical cluster (assuming isotropic distribution surrounding the sphere) and with the origin of co-ordinates at the center of the cluster in steady state is given by

$$\nabla^2 T = 0 \quad \text{in} \quad \frac{D_c}{2} < r < \infty \quad (10)$$

which considering the boundary conditions  $T(\frac{D_c}{2}) = T_p$ ; and  $T(\infty) = T_\infty$ , becomes

$$T(r) = T_\infty + \frac{(T_p - T_\infty) D_c}{2} \frac{D_c}{r} \quad (11)$$

Because we are interested not only in the peak of temperature at the surface of the cluster  $T_p$  but also the resolution of the temperature profile, it is interesting to introduce the concept of full width at half maximum (FWHM) which is equal to the distance from the peak which attain a half of its maximum value. In other words, it is the width of the radial distance measured between those points on the temperature-axis which are half the maximum temperature. From Eq.(11) the FWHM  $\Delta_{fwhm}$  is given by

$$\Delta_{fwhm} = 2D_c \quad (12)$$

As it is seen the  $\Delta_{fwhm}$  for a pure conductive temperature distribution is only dependent on the size of the cluster and if the cluster has a small diameter also the FWHM. As an illustrative example, Fig. 4 shows the  $\Delta_{fwhm}$  for a sphere with a diameter  $D_c = 100\mu\text{ m}$   $T_\infty = 298\text{ K}$  and a cluster surface temperature  $T_p = 348\text{ K}$ .

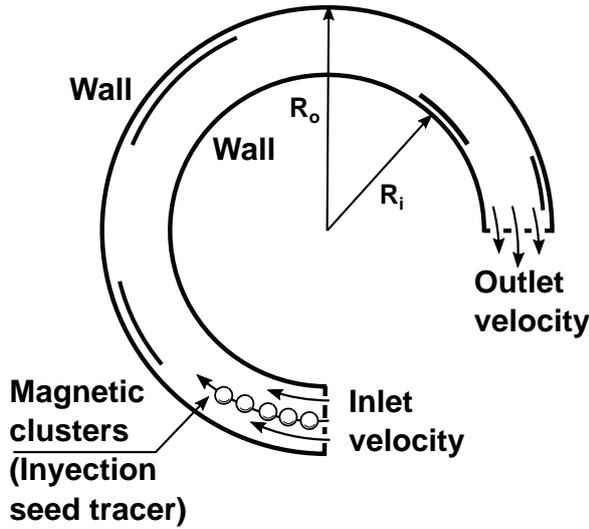


FIG. 5. Geometry for the computational simulation

#### IV. COMPUTATIONAL SIMULATION

Computational fluid dynamics (CFD) simulations were performed using Ansys Fluent CFD software version 14.

##### • Problem description:

The problem to be considered is shown schematically in Fig. 5. Water was considered inside an annular pipe with outer and inner radius of 2 cm and 1 cm, respectively, where in addition, a continuous current of water with a velocity 0.2 m/s was used. The temperature of the stream water was 298 K. Particles with a diameter 100  $\mu\text{m}$  were injected and transported by advection by the flow. The temperature of each particle was 348 K and was kept constant, i.e., 50 K higher than the water, Boussinesq approximation was used to simulate the natural convection surrounding the sphere. Some sequence of the simulation is depicted in Fig. 6 where it is shown the temperature profile surrounding two spheres following the stream lines. The left side of Fig. 6 shows the expected thermal image visualized by a infrared camera operating in a full range continues range of temperatures; and the right side, if the visualization of the camera is limited to detect infrared rays from temperatures equal or higher than 345 K. Finally, Fig. 7 is the plot of the temperature distribution surrounding one particle, where by comparison with the Fig. 4, shows that the approximation of conductive heat transfer is a good approximation and then thermal effects are not affecting the velocity profile.

#### V. CONCLUSIONS

In this work a novel approach is investigated for Particle Image Velocimetry (PIV) in which magnetic clusters are used together with alternating magnetic field which result in local hyperthermia of the cluster owing to the dissipative power from the motion in the viscous medium. The heat radiation emitted by the particles is detected by infrared cameras or other detectors. Because the most recent advances in detection and tracking in thermal infrared imagery, Thermal-PIV by the use of hyperthermal magnetic clusters allow a unique feature, namely, the visualization of flows through opaque bodies which, needless to say, could have important applications not only in the industry but in medicine.

##### NOMENCLATURE:

$c_1$	= constant
$d_p$	= diameter of the nanoparticle
$D_c$	= diameter of the cluster
$FWHM$	= full width at half maximum
$g$	= gravity
$h$	= heat transfer coefficient
$H_o$	= amplitude magnetic field
$M_s$	= saturation magnetization
$\mathbf{Nu}$	= Nusselt number
$\mathbf{Ra}$	= Rayleigh number
$P$	= volumetric power
$R$	= radius of the pipe
$S$	= surface
$T$	= temperature
$V$	= volume

##### Greek symbols

$\phi$	= volume fraction of solids
$\kappa$	= thermal conductivity
$\kappa_B$	= Boltzmann's constant
$\nu$	= kinematic viscosity
$\rho$	= density
$\mu_o$	= permeability of free space;
$\chi_o$	= magnetic susceptibility
$\xi$	= Langevin parameter, defined by Eq.(??)
$\tau$	= time constant
$\omega$	= magnetic cyclic frequency

##### subscripts

$c$	= cluster
$c$	= convection
$\kappa$	= conductive
$f$	= fluid
$i$	= inlet
$m$	= magnetic
$o$	= reference, outlet
$p$	= particle
$t$	= total
$\infty$	= quiescent temperature of the fluid

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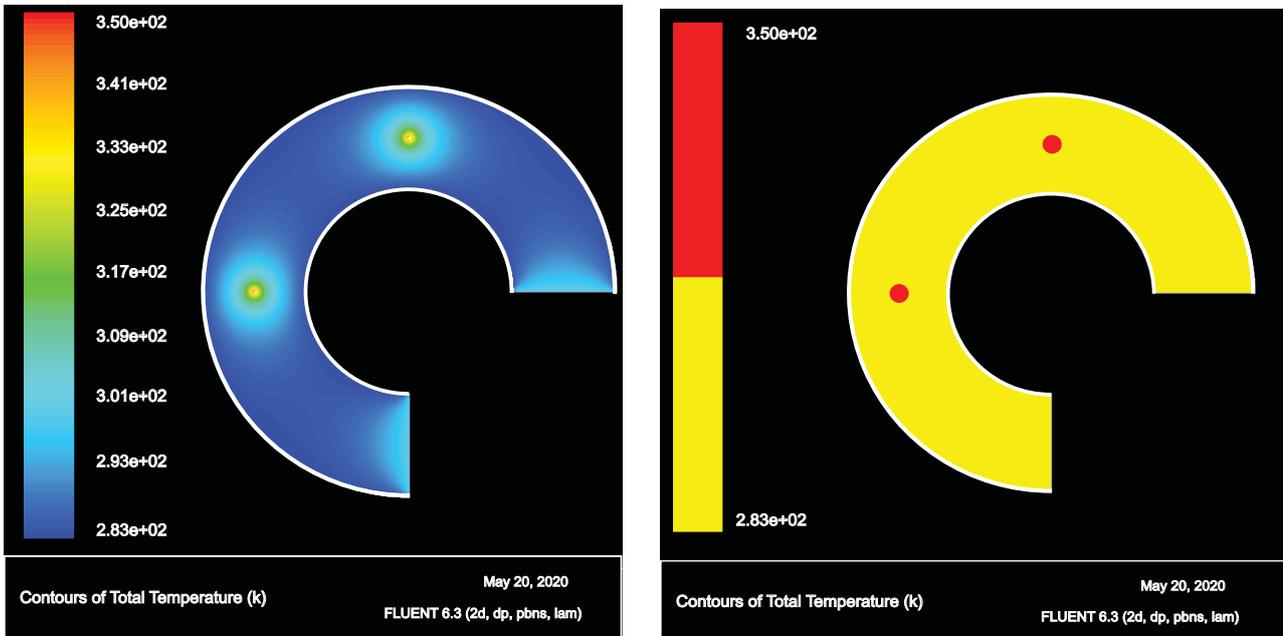


FIG. 6. Temperature distribution around to magnetic clusters from the CFD simulations

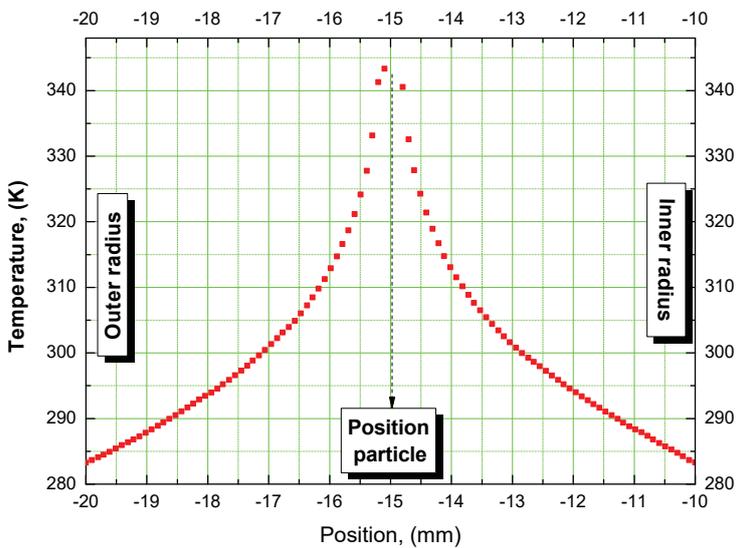


FIG. 7. Temperature distribution around one cluster from the CFD simulations

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## VI. REFERENCES

- [1] Hiergeist R; Andra W; Buske N; Hergt R; Hilger I; Richter U; Kaiser W. 1999. Journal of Magnetism and Magnetic Materials, Volume 420.
- [2] Zubarev A.Y; Iskakova L.Y; Safronov A.P; Krekhno R.V; Kuznetsov D; Beketov I.V. 2019. Positive feedback of interparticle interaction on magnetic hyperthermia, Journal of Magnetism and Magnetic Materials, Volume 489
- [3] Lazic D; Malaescu I; Bunoiu O.M; Marin I; Popescu F.G; Socoliuc V; Marin C.N. 2020. Investigation of therapeutic-like irradiation effect on magnetic hyperthermia characteristics of a water-based ferrofluid with magnetite particles, Journal of Magnetism and Magnetic Materials, Volume 502.
- [4] Salati A; Ramazani A; Kashi M:A. 2020. Tuning hyperthermia properties of FeNiCo ternary alloy nanoparticles by morphological and magnetic characteristics, Journal of Magnetism and Magnetic Materials, Volume 498.
- [5] Kashevsky B.E; Kashevsky S; Terpinskaya T.I; Ulashchik V.S. 2019. Magnetic hyperthermia with hard-magnetic nanoparticles: In vivo feasibility of clinically relevant chemically enhanced tumor ablation, Journal of Magnetism and Magnetic Materials, Volume 475.

- [6] Zhang W; Yu X; Li H; Dong D; Zuo X; Wu C.W. 2019. Magnetic nanoparticles with low Curie temperature and high heating efficiency for self-regulating temperature hyperthermia, *Journal of Magnetism and Magnetic Materials*, Volume 489.
- [7] Berg A. 2016. Detection and Tracking in Thermal Infrared Imagery. Linköping studies in science and technology. Thesis. No. 1744. Licentiate's Thesis. Linköping University
- [8] Fishenden M; Saunders A.A. An Introduction to Heat Transfer. Oxford University Press, London, 1950.
- [9] Rosensweig R.E. 2020. Heating magnetic fluid with alternating magnetic field. *Journal of Magnetism and Magnetic Materials* 252. 370-374.
- [10] Landau L.D; Lifshitz E.M. 1959. *Fluid Mechanics*. Pergamon Press. London.
- [11] Marion J.B; Thornton S.T. 1988. *Classical Dynamic of Particles & Systems*. Third edition. Harcourt Brace Jovanovich, Publishers
- [12] Rohsenow W.M; Hartnett J.P. 1973. *Handbook of Heat Transfer*. McGraw-Hill