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NATURAL CONVECTION IN ENCLOSURES CONTAINING LEAD-BISMUTH AND LEAD

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ABSTRACT

The design of liquid metal reactors such as Encapsulated Nuclear Heat Source (ENHS) [1] which are based predominantly on the flow generated by natural convection effects demands knowledge of velocity and temperature fields, distribution of the local Nusselt numbers and values of the average Nusselt numbers for small coolant velocity regimes.

Laminar natural convection in rectangular enclosures with different aspect ratios, containing lead-bismuth and lead is studied numerically in this paper. The numerical model takes into account variable properties of the liquid metals as in [2].

The developed correlation for average Nusselt numbers is presented. It is concluded that average Nusselt numbers are lower than in "normal" fluids (air, water and glycerol [2,3,4]) for the same values of Rayleigh numbers. However, the heat flux, which can be achieved, is greater due to the high thermal conductivity of liquid metals. Some specific features of the flow fields generated by natural convection in liquid metals are presented. Their consequences on the design of heat exchangers for liquid metals are discussed.

An application of the obtained results to the design of a new type of steam generator, which integrates the intermediate heat exchanger and secondary pool functions of the ENHS reactor, is presented.

NOTATION

c_p - specific heat of the fluid, J/kg K

g - acceleration due to gravity, m /s ^{2}

H - height of the enclosure, H = 0.038 m

V - velocity vector, m/s

u - velocity along x, m/s

v - velocity along y, m/s

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k_f - thermal conductivity of the fluid, W/mK
N - number of partitions in the enclosure
Nu - local Nusselt number
$\overline{Nu}$ - average Nusselt number
p - pressure, N/m^2
Pr - Prandtl number based on T_o, $\mathrm{Pr} = \nu / a$
Ra - Rayleigh number,
$Ra = g\beta(T_h - T_c)W^3 / \nu\alpha$,
properties are based on T_o
T - temperature, ° C
T_C - temperature in ° C
T_c - temperature of the cold vertical wall, ° C
T_h - temperature of the hot vertical wall, ° C
T_K - temperature in K
T_o - average temperature
$T_o = (T_h + T_c) / 2$, ° C
W - width of the enclosure,
W = 0.038, 0.019 and 0.0095 m

Greek symbols

α - thermal diffusivity,
$\alpha = k_f / \rho c_p$, m^2/s
β - thermal expansion coefficient of the fluid, 1/K
ρ - density of the fluid, kg/m^3
ν - kinematic viscosity of the fluid, m^2/s
μ - dynamic viscosity of the fluid, kg / m s

INTRODUCTION

Natural convection in enclosures has been receiving considerable attention due to its numerous applications such as in thermal design of buildings, nuclear reactor design, cooling of electronic equipment and solar collectors. One of the first experimental and numerical studies was presented by [5-7]. An overview of later results was presented by [8-11]. Results of natural convection in enclosures are also used as bench mark data for validation of various numerical methods for solving Navier-Stokes equations (see [12-14]). In most of the papers the working fluid used was air, but in some cases water and oils were used as well.

Laminar natural convection in rectangular enclosures with different aspect ratios, containing lead-bismuth and lead is studied numerically in this paper. The reason is that the design of liquid metal reactors such as Encapsulated Nuclear Heat Source (ENHS) [1] demands knowledge of velocity and temperature fields, distribution of the local Nusselt numbers and values of the average Nusselt numbers for small coolant velocity regimes.

The two opposite vertical walls of the enclosure were isothermal at different temperatures. The horizontal sides were adiabatic. The numerical model was based on the finite volume method as in [15]. The steady two-dimensional model accounted for the variable thermophysical properties of the fluid as in [2,16]. The velocity and temperature fields and the distribution of the local and average Nusselt numbers were found as a function of the Rayleigh ($3000<Ra<10^6$) numbers.

An application of the obtained results to the design of a new type of steam generator, which integrates the intermediate heat exchanger and secondary pool functions of the ENHS reactor, is presented at the end.

NUMERICAL METHOD

A two dimensional numerical simulation of natural convection in rectangular enclosures with different aspect ratios was applied. The equations for a fluid with variable properties were used. The continuity and momentum equations are

$$\frac{\partial}{\partial x}\rho u+\frac{\partial}{\partial y}\rho v=0 \tag{1}$$

$$\frac{\partial}{\partial x}\rho uu+\frac{\partial}{\partial y}\rho vu=\frac{\partial}{\partial x}[2\mu\frac{\partial u}{\partial x}-\frac{2}{3}\mu(\nabla V)]+\frac{\partial}{\partial y}[\mu(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})]-\frac{\partial p}{\partial x} \tag{2}$$

$$\frac{\partial}{\partial x}\rho uv+\frac{\partial}{\partial y}\rho vv=\frac{\partial}{\partial x}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})]+\frac{\partial}{\partial y}[2\mu\frac{\partial v}{\partial y}-\frac{2}{3}\mu(\nabla V)]-\frac{\partial p}{\partial y}+\rho g \tag{3}$$

The energy equation is

$$\frac{\partial}{\partial x}\rho uc_pT+\frac{\partial}{\partial y}\rho vc_pT=\frac{\partial}{\partial x}(k_f\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k_f\frac{\partial T}{\partial y}) \tag{4}$$

The properties of the lead-bismuth were specified as functions of temperature as follows:

$\rho=10719.817\text{-}1.222*T_C+4.217*10^{-5}*T_C^{\,2}-1.858*10^{-7}*T_C^{\,3}$ [kg/m^3], (5)
valid for 130°C<T_c<1000°C,
$\beta=1.1725*10^{-4}-2.7814*10^{-3}*T_C^{\,-1}+1.0665*T_C^{\,-2}-128.7297*T_C^{\,-3}$[1/K] (6)
valid for 130°C<T_c<1000° C,

$\mu=4.915*10^{-3}-1.621*10^{-5}*T_C+2.447*10^{-8}*T_C^{\,2}-1.288*10^{-11}*T_C^{\,3}$[kg/m s], (7)
valid for 150°C<T_c<833°C,
$k=19.0441-0.059*T_K+1.112*10^{-4}*T_K^{\,2}-5.471*10^{-8}*T_K^{\,3}$[W/m K], (8)
valid for 130°C<T_C<700°C,
$C_p=146.51$ [J/kgK], valid for 130°C to 700°C. (9)

Most of the lead-bismuth property data is presented by [17-19].

The properties of lead were specified as functions of temperature as:

$\rho=10947.0885\text{-}1.0338*T_C-1.6476*10^{-4}*T_C^{\,2}$ [kg/m^3], (10)
valid for 371.1°C<T_C< 704.4°C
$\beta=9.464318*10^{-5}+3.783627*10^{-8}*T_C+7.2206*10^{-12}*T_C^{\,2}$ [1/K], (11)
valid for 371.1°C<T_C< 704.4°C,
$\mu=8.7734*10^{-3}-3.0515*10^{-5}*T_C+4.5478*10^{-8}*T_C^{\,2}-2.4278*10^{-11}*T_C^{\,3}$[kg/m s], (12)
valid for 343.0°C<T_C< 704.4°C,
$k=31.5824-4.6967*10^{-2}*T_K+4.5425*10^{-5}*T_K^{\,2}-1.4410*10^{-8}*T_K^{\,3}$[W/m K], (13)
valid for 327.44°C<T_C<1081.84°C,
$C_p=791.1979-2.3706*T_K+2.9336*10^{-3}*T_K^{\,2}-1.2058*10^{-6}*T_K^{\,3}$, (14)
valid for 327.44°C<T_C<926.8°C,

The property data for lead was taken from [17, 20-22].

The discrepancy of experimental data for lead and lead-bismuth properties, especially for thermal conductivity and viscosity, introduces uncertainties in the applied numerical method. Also, viscosity could be sensitive to impurities in a real installation. The mentioned uncertainties could be taken into consideration by repeating calculations with different expressions for properties.

In all cases the height of the enclosure was H=0.038 m. The width of the enclosure was varied, W=0.038 m, W=0.019 m and W=0.0095 m, resulting in aspect ratios H/W= 1, 2 and 4, respectively. The number of applied uniform collocated cells in horizontal and vertical direction for each case is presented in Table 1.

The horizontal walls were assumed to be adiabatic with he vertical walls being at different isothermal temperatures. The imposed temperatures of the vertical walls and resulting Rayleigh numbers are presented in Table 1. The left vertical side was always at the higher temperature.

The SIMPLE procedure [15] was used to solve the set of equations. For all calculated cases 5000 SIMPLE iterations were used. For the convective terms the central difference scheme was used with the "deferred correction" similar to that in [23], while the diffusion terms were approximated by using a second order central difference approximation. More details about the numerical procedure can be found in [16].

However, application of the second order central difference scheme for the convective terms and enclosures filled with liquid metals caused numerical difficulties. To obtain convergence, it was necessary to suppress them (they were multiplied with 0.001). The effect is the same as if the first order upwind scheme was used. Also, the criteria to stop iterations for the pressure equation (in fact mass balance equation) was that residuals need to be below 10^{-10}. The number of iterations for the pressure equation was limited to 1000. In the case of "normal" fluids (air, water, oil) this criteria and the limit of iterations for pressure could be 10^{-2} and 20-100, respectively. Usually 2-5 iterations are necessary near the end of calculation for the pressure equation and "normal" fluids.

DISCUSSION OF THE RESULTS

The calculated average Nusselt numbers are presented in Table 1 and Figure 1. It could be concluded that agreement of the results for the coarse grid (76X76 cells) and twice finer grid (152X152 cells) is good (compare results for the cases 1-6 in Table 1 for the lower range of the lead-bismuth temperatures, T_c=220°C). The rest of the results for the square enclosure (H/W=1) were obtained with the coarse grid (cases 7-16, for the higher range of temperatures, T_c=540°C). All results for the narrow enclosures (H/W=2 and 4) were obtained with the fine grid and higher range of temperatures (T_h=560°C).

The average Nusselt numbers for lead and lead-bismuth for the enclosures with the aspect ratios H/W=1 and 2 could be correlated with one curve (see Figure 1):

$$\overline{Nu} = 0.1346 * Ra^{0.2735} \qquad \text{valid for } 30000<Ra<10^6 \quad (15)$$

In the case of the tall enclosure (H/W=4) the average Nusselt numbers are lower and the discrepancy between results for lead and lead-bismuth is noticeable. The correlation is:

$$\overline{Nu} = 0.1281 * Ra^{0.2627} \qquad \text{valid for } 3000<Ra<250000 \quad (16)$$

Both correlations can be compared with the correlation developed by [4] for water and valid for air:

$$\overline{Nu} = 0.297 * Ra^{1/4} * (H/W)^{-1/4} * (N+1)^{-1} \qquad (17)$$

The conclusion is that average Nusselt numbers for liquid metals are 50%-60% lower than for the "normal" fluids. This is in agreement with the review of experimental data [19] for natural convection in an unbounded volume around bodies of various shapes in liquid metals.

However, the heat fluxes are much higher in the case of liquid metals due to their high thermal conductivity (see Table 1). It could be concluded that the narrow enclosure provides higher heat fluxes for the same temperature differences of the opposite walls although the convection effects (Nusselt numbers) are lower. This is because thermal conduction resistance is smaller for the narrower enclosures. This finding indicates the direction for the design of the more compact heat exchangers for liquid metals.

The advantage of the numerical approach is that all details of the velocity and temperature distribution and distribution of the local Nusselt numbers is available. The streaklines and temperature fields for the square enclosures filled with lead-bismuth are presented in Figure 2. The main difference from the well-known flow structure in "normal" fluids is the presence of the vortices in the corners. This indicates that sharp corners need to be avoided in liquid metal heat exchanger design. The temperature field stratifies in the core of the enclosure and the thermal boundary layer is thinner with the increase of the Rayleigh number (as in "normal" fluids).

The corresponding local Nusselt number distributions and vertical velocity components in the middle horizontal cross-section (H/2=0.019 m) are presented in Figures 3 and 4. They are indicating locations of the cold and hot stream impingement points at vertical walls (see locations of the maximum local Nusselt numbers in Figure 3). The velocity profiles in Figure 4 show that boundary layer flow is dominant, while the core of the enclosure is almost stagnant. Both Figures are similar to the distributions obtained with "normal" fluids (see for example [2]).

Table 1 List of calculated cases, vertical wall temperatures, Rayleigh numbers, average Nusselt numbers and heat fluxes

Case No.	Width mm	Fluid	Cells	T_h °C	T_c °C	Rayleigh number	Average Nusselt	Heat Flux

							number	KW/m^2
1	38	Le-Bi	76X76	225	220	198400	4.22	5.79
2	38	Le-Bi	152X152	225	220	198400	4.22	5.79
3	38	Le-Bi	76X76	230	220	398700	5.09	14.04
4	38	Le-Bi	152X152	230	220	398700	5.05	13.92
5	38	Le-Bi	76X76	240	220	804700	6.16	34.18
6	38	Le-Bi	152X152	240	220	804700	6.08	33.71
7	38	Le-Bi	76X76	541	540	47500	2.62	1.05
8	38	Le-Bi	76X76	542	540	94900	3.11	2.48
9	38	Le-Bi	76X76	545	540	237100	3.92	7.86
10	38	Le-Bi	76X76	550	540	473900	4.75	19.05
11	38	Le-Bi	76X76	560	540	946300	5.82	46.92
12	38	Lead	76X76	545	540	193100	3.77	7.78
13	38	Lead	76X76	550	540	388000	4.53	18.69
14	38	Lead	76X76	560	540	783000	5.51	45.42
15	38	Lead	76X76	550	530	769000	5.50	45.33
16	38	Lead	76X76	560	530	1164000	6.19	76.60
17	19	Le-Bi	76X152	545	540	29600	2.01	8.06
18	19	Le-Bi	76X152	560	540	118300	3.07	49.56
19	19	Le-Bi	76X152	560	500	357000	4.44	210.79
20	19	Le-Bi	76X152	560	460	598400	5.04	392.06
21	19	Le-Bi	76X152	560	400	963000	5.71	688.15
22	19	Lead	76X152	545	540	24100	1.96	8.10
23	19	Lead	76X152	560	540	97900	3.00	49.50
24	19	Lead	76X152	560	500	283000	4.25	80.08
25	19	Lead	76X152	560	460	453500	4.77	394.96
26	19	Lead	76X152	560	400	680700	5.29	704.66
27	9.5	Le-Bi	38X152	545	540	3700	1.17	9.34
28	9.5	Le-Bi	38X152	560	540	14800	1.46	47.03
29	9.5	Le-Bi	38X152	560	500	44600	2.46	233.68
30	9.5	Le-Bi	38X152	560	400	120400	2.58	622.37
31	9.5	Le-Bi	38X152	560	300	195600	3.14	1163.8
32	9.5	Le-Bi	38X152	560	200	266700	3.62	1744.7
33	9.5	Lead	38X152	545	540	3000	1.14	9.43
34	9.5	Lead	38X152	560	540	12200	1.67	54.95
35	9.5	Lead	38X152	560	500	35400	1.77	176.00
36	9.5	Lead	38X152	560	400	85091	2.29	609.08

Figure 1 Average Nusselt numbers as a function of Rayleigh numbers and enclosure aspect ratios (H/W=1, 2 and 4)

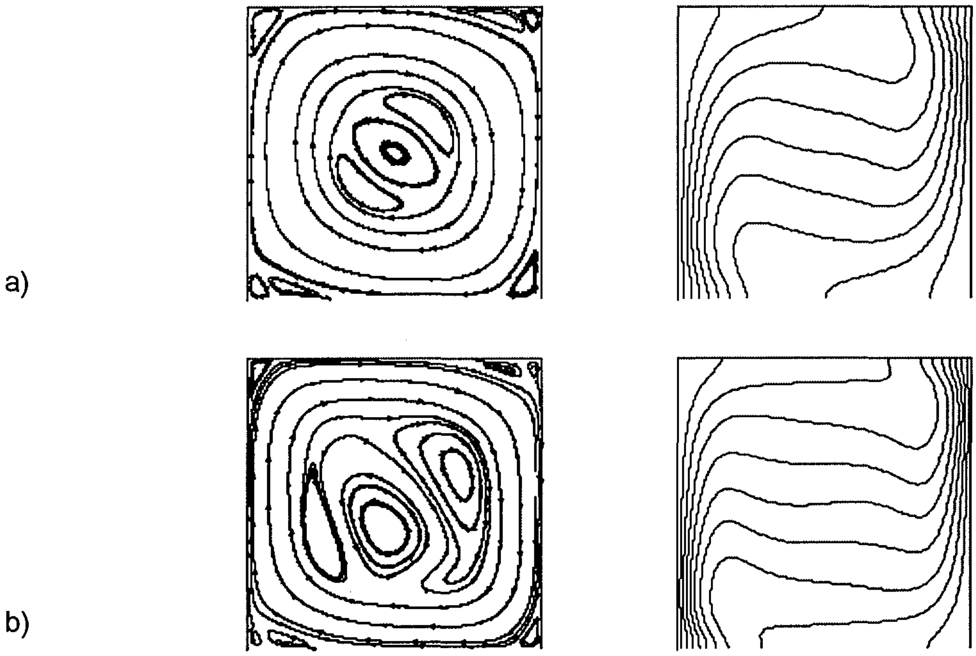

Figure 2 Streak lines and temperature distribution in the square cavity filled with lead-bismuth a) for case 9, Th=545°C, Tc=540°C, Ra=237100, b) for case 11, Th=560°C, Tc=540°C, Ra=946300.

Figure 3 Local Nusselt number distributions on the hot and cold vertical walls for cases 9, 10 and 11

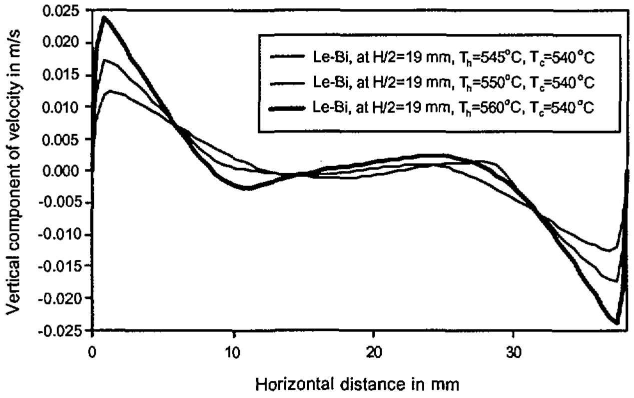

Figure 4 Distribution of vertical velocity components in the middle horizontal cross-section (H/2=0.019 m) for cases 9, 10 and 11

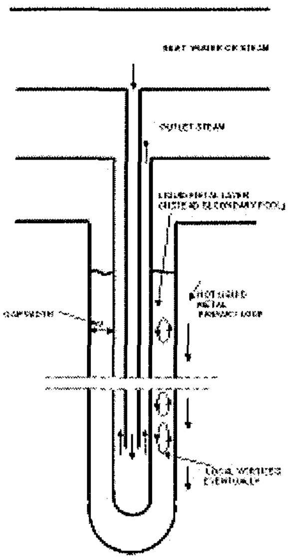

Figure 5 Tube in Tube Stem Generator Concept

APPLICATION OF THE RESULTS TO THE TUBE IN TUBE STEAM GENERATOR CONCEPT

The idea for the novel tube in tube steam generator concept is generated in the framework of the first year research on ENHS (see [24]). The concept with the water supply tube within the steam exit tube (the first two tubes around vertical axis in Figure 5) is already known and is now proposed for commercial power plants, as in SWBR-75 reactor plant design (see [25]). The application of the protective layers (intermediate materials) between the liquid metal loop and the water in the steam generator is also a well known concept.

The main difference and novelty of the concept proposed in the framework of the ENHS design is that an additional tube (third one) with an intermediate layer (in it) could be applied around the already known tube in tube steam generator configuration. It is in fact a combination of the two previously mentioned concepts.

The proposed type of steam generator would be located directly in the primary loop while still maintaining separation of primary lead, or lead-bismuth. The steam generator would consist of many vertical tubes inserted in tubes filled with a liquid metal (as in Figure 5), or porous material, or elastic fins.

This novel steam generator allows servicing and replacement of the steam generator inner tubes because the inner tubes can be pulled out and immersed again as long as the lead-bismuth in the outer tubes is in the liquid state, or porous media can be removed and inserted again. Both, the protective feature of the secondary loop and the ability to replace the steam generator in the present ENHS concept with the pool and secondary loop are also present in this novel concept of the steam generator. However, instead of having a pool and a secondary loop of liquid lead providing the natural circulation many small vortices are created inside the gap filled with the secondary lead (see local vortices in Figure 5). To promote these local vortices, horizontal or inclined (in fact conical) spacers could be provided along the tube length.

The results obtained in this paper can be used as a part of the effort to optimize the novel tube in tube steam generator configuration. The preliminary results suggest that narrow gap between the two outer tubes could provide more compact design and efficient heat transfer. In that case the heat transfer would predominantly rely on heat conduction instead on natural convection effects. This is possible due to the high thermal conductivity of liquid metals. However, the introduction of various spacers which can additionally promote natural convection in the intermediate layer should not be excluded as an option (see [3]).

CONCLUSIONS

Several conclusions relevant for numerical modeling of the natural convection in liquid metals, flow structures inside the enclosures filled with liquid metals and development of the liquid metal heat exchangers were obtained in this paper.

To obtain convergence it was necessary to suppress the second order terms generated from the central difference scheme for the convective terms. In fact the first order upwind scheme was used. Also, the criteria to stop iterations for the pressure equation was that residuals need to be below 10^{-10}. The number of iterations for pressure was limited to 1000. These criteria are much stricter then for "normal" fluids. Further attempts to introduce higher order numerical schemes and optimize the number of necessary iterations and convergence criteria are necessary.

The main difference from the well-known flow structure in rectangular enclosures filled with "normal" fluids is the presence of the vortices in the corners. This indicates that sharp corners are not suitable for liquid metal heat exchanger design. This is important if we want to avoid the presence of stagnation regions.

The results of natural convection simulation suggest that a narrow gap between the two outer tubes of the tube in tube steam generator concept could provide more compact design and efficient heat transfer. In that case the heat transfer would predominantly rely on heat conduction instead on natural convection effects. This is possible due to the high thermal conductivity of liquid metals.

REFERENCES

[1] E. Greenspan, D. Saphier, D. C. Wade, J. Sienicki, M. D. Carelli, L. Conway, M. Dzodzo, N. W. Brown, Q. Hossain, "Promising Design Options for the Encapsulated Nuclear Heat Source Reactor", Submitted to ICONE-9, (2001)

[2] D.M. Cuckovic-Dzodzo, M.B. Dzodzo, M.D. Pavlovic, "Laminar natural convection in a fully partitioned enclosure containing fluid with nonlinear thermophysical properties", Int. J. of Heat and Fluid Flow, Vol. 20, pp. 614-623, November (1999)

[3] M. B. Dzodzo, "Visualization of laminar natural convection in romb-shaped enclosures by means of liquid crystals", published in: *Imaging in Transport Processes*, editors Sideman S., Hijikata K., Yang W. J., Begel House Publishers, NY, Chapter 15, pp. 183-193, (1993)

[4] T. Nishimura, M., Shiraishi, F. Nagasawa, Y Kawamura, "Natural convection heat transfer in enclosures with multiple vertical partitions", Int. J. Heat and Mass Transfer, Vol. 31, pp 1679-1686, (1988)

[5] J. W. Elder, "Laminar free convection in a vertical slot", J. Fluid Mech., Vol. 23, part 1, 77-98, (1965)

[6] J. W. Elder, "Turbulent free convection in a vertical slot", J. Fluid Mech., Vol. 23, part 1, 99-111, (1965)

[7] J. W. Elder, "Numerical experiments with free convection in a vertical slot", J. Fluid Mech., Vol. 24, part 4, 823-843, (1965)

[8] S. Ostrach, "Natural convection in enclosures", Advances in Heat Transfer, Hartnett J.P. and Irvine T.F., (eds.), Academic Press, New York, Vol. 1, (1972)

[9] S. Ostrach, "Natural convection heat transfer in cavities and cells", *Heat Transfer-82*, Vol. 1, 365-379, Munchen, (1982)

[10] I. Catton, "Natural convection in enclosures", *Proc. 6th. Int. Heat Transfer Conference*, Vol. 6, 13-43, (1978)

[11] K. T. Yang, "Natural convection in enclosures", In *Handbook of Single-Phase Convective Heat Transfer*, Kakac S., Shah R. K., Aung W., (eds.). John Wiley & Sons, New York, 13-1 - 13-51, (1987)

[12] G. de Vahl Davis and I. P. Jones, "Natural convection in a square cavity: a comparison exercise", Int. J. Numer. Meth. Fluids, Vol. 3, 227-248, (1983)

[13] G. de Vahl Davis, "Natural convection of air in a square cavity: a bench mark numerical solution", Int. J. Numer. Meth. Fluids, Vol. 3, 249-264, (1983)

[14] M. Hortmann, M. Peric, G. Scheurerer, "Finite Volume Multigrid Prediction of Laminar Natural Convection: Bench-Mark Solutions", Int. J. Numer. Meth. Fluids, Vol. 11, 189-207, (1990)

[15] S. V. Patankar, and D. B. Spalding, "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows", Int. J. Heat Mass Transfer, Vol. 15, 1787-1806, (1972)

[16] D. M. Cuckovic-Dzodzo, M. B. Dzodzo, M. D. Pavlovic, "A matematical model and numerical solution for the conjugated heat transfer in a fully partitioned enclosure containing the fluids with variable nonlinear thermophysical properties", Theoretical and Applied Mechanics, Yugoslav Society of Mechanics, Vol. 24, 29-54, (1998)

[17] R. N. Lyon and H. F. Poppendiek, "Liquid-Metal Heat Transfer", Chapter 5 in Liquid-Metals Handbook, Editor in Chief, R. N. Lyon, "Liquid Metals Handbook," 2d ed. (revised), Atomic Energy Commission, Department of the Navy, Washington, D.C., pp. 184 - 212., (1954)

[18] N. A. Nikol'skii, N. A. Kalakutskaya, I. M. Pchelkin, T. V. Klassen and A. Vel'tishcheva, "Thermal and Physical Properties of Molten Metals and Alloys", AEC-tr-4511, Problems of Heat Transfer, M. A. Mikheav, Ed., Academy of Sciences SSSR, Moskva, pp. 1-38., (1959)

[19] S. S. Kutateladze, V. M. Borishanskii, I. I. Novikov and O. S. Fedynskii, " Liquid-Metal Heat Transfer Media", Supplement No. 2 of the Soviet Journal of Atomic Energy Atomnaia Energiia, Atomic Press, Moscow, 1958, Translated from Russian, Consultants Bureau, Inc., New York, (1959)

[20] Y. S. Touloukian, S. C. Saxena and P. Hestermans, "Thermo-physical Properties of Matter Viscosity", vol. 11, The TPRC Data Series, IFI/Plenum, New York, (1970)

[21] Y. S. Touloukian, R. W. Powell, C. Y. Ho, P. G. Klemens, "Thermo-physical Properties of Matter, Volume 1: Thermal Conductivity - Metallic Elements and Alloys", The TPRC Data Series, IFI/Plenum, New York, pp 175-191, (1970)

[22] Y. S. Touloukian, E. H. Buyco, "Thermo-physical Properties of Matter. Specific Heat – Metallic Elements and Alloys", vol. 4, The TPRC Data Series, IFI/Plenum, New York, (1970)

[23] P. K. Khosla, S. G. Rubin, "A diagonally dominant second-order accurate implicit scheme", Computers and Fluids, Vol. 2, 207-209, (1974)

[24] E. Greenspan, et al., "First Year Final Report of the NERI/DOE ENHS Project", UC Berkeley, Nuclear Engineering Department, (2000)

[25] V. S. Stepanov, N. N. Klimov, M. L. Kulikov, S. K. Leguenko, V. I. Chitaikin, B. F. Gromov, G. I. Toshinski and O. G. Grigorev, "Perspective Reactors with Lead-Bismuth Liquid Metal Coolant", Proceedings of the Conference "Heavy Liquid Metal Coolants in Nuclear Technology", held on October 5-9, 1998, Volume 2, pp. 377-385, State Scientific Center of Russian Federation Institute for Physics and Power Engineering named after Academician A. I. Leipunsky, Obninsk, (1999)