Thermal conductivity of iron and nickel during melting:
Implication to Planetary liquid outer core

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Abstract

We report the measurements of the thermal conductivity ($\kappa$) of iron (Fe) and nickel (Ni) at high pressures and high temperatures. $\kappa$ values are estimated from the temperature measurements across the sample surface in a laser heated diamond anvil cell (LHDAC) and using the COMSOL software. Near-isothermal $\kappa$’s are observed to increase with pressure in both the metals due to the increase of density of the pressed metals. In both metals $\kappa$’s are observed to follow a sharp fall during melting at different pressure points and are consistence with the other multi-anvil measurements. Constant values of $\kappa$ in these metals during melting at different pressures reveal the loss of long range order, which creates independent movement of atomic metals. The melting temperature measured in these metals from the sudden drop of $\kappa$-values are in a good agreement with the other melting measurements in LHDAC. The results obtained in this study is expected to provide an insight to the studies on the planets Mercury and Mars and their interior.

Keywords: Laser heated diamond anvil cell, COMSOL, Thermal conductivity, High pressure effects, Constant thermal conductivity, Geodynamo

I. INTRODUCTION

Seismological and geophysical studies revealed that the elements having high binding energy like Fe and Ni in their pure phase or in the alloy form with light elements (C, S, Si, and O etc.) are present in the planetary core[1–18]. These materials are predicted to be present in liquid state at the outer core of the planets. The knowledge of the transport properties of Fe and Ni at high pressure (HP) and high temperature (HT) conditions are essential for better understanding the generation of the magnetic field and the heat loss from Earth’s core. Therefore, the measurement of the thermal conductivity ($\kappa$) of these materials at extreme conditions of pressure and temperature are very important for the understanding the dynamics of the planetary interior. The value of the $\kappa$ determines the age of the inner core (low value implies older core). Stacey et al. predicted a lower value of $\kappa\sim 28-29 \text{ W m}^{-1}\text{K}^{-1}$ from the theoretical calculations on Fe – Ni – Si alloy[19, 20] by extrapolating near ambient conditions data. Later the first principles calculations using density functional theory reported the value of $\kappa$ to be very high $\sim 160-200 \text{ W m}^{-1}\text{K}^{-1}$[21–

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at the Earth’s core conditions. In their studies mostly they considered the electron and phonon contribution terms independently for the anharmonicity effect and the change in the Fermi surface, respectively. Recently Xu et al. [27] computed $\kappa$ to be $77\pm 10 \text{ W m}^{-1}\text{K}^{-1}$ at the Earth’s outer core conditions considering both the electron-phonon ($e$-$ph$) and electron-electron ($e$-$e$) scattering contributions to electrical and thermal conductivity in solid $hcp$ – iron. The thermal conductivity in the outer-inner core boundary on C, O, Si and S doped Fe + 10% Ni at a rate 30% ternary systems were calculated in the range of $105 - 140 \text{ W m}^{-1}\text{K}^{-1}$ very recently by Zidane et al.[28]. The above study did not discuss about the Bloch-Gruneisen law in combination with Mathiessen’s rule to describe the phononic contribution, however they claimed that upon consideration of the phononic contribution, the thermal conductivity will decrease.

The experimental determination of the thermal conductivity at extreme conditions of pressure and temperature are very challenging and rare [29–33]. Thermal conductivity of $Fe$ was determined directly from the measurements of the temperature and heat propagation [31–33] in a laser heated diamond anvil cell (LHDAC). There are several reports of $\kappa$, estimated indirectly, from the high pressure and high temperature electrical resistivity measurements using multi anvil cell (MAC) [34–38] and diamond anvil cell (DAC) [29, 30, 39]. The $\kappa$ was estimated from the resistivity ($\rho$) data employing Wiedemann-Franz-Lorenz law. From resistivity measurement, Gomi et al. predicted $\kappa$ for $Fe$ to be higher than 90 $\text{ W m}^{-1}\text{K}^{-1}$ at Earth’s outer core conditions from DAC experiments combined with theoretical calculations [29]. Later, from the resistivity measurements in LHDAC, Ohta et al. estimated a high value of $\kappa$ ($\sim 226^{+72}_{-31} \text{ W m}^{-1}\text{K}^{-1}$) of $Fe$ at core mantle boundary conditions based on resistivity saturation of $hcp$ – $Fe$. These diamond cell experiments are well supported by the theoretical calculations [21–26]. In contrast to the above studies all the MAC experiments reported $\kappa$ values in the range 39-70 $\text{ W m}^{-1}\text{K}^{-1}$ for solid and liquid $Fe$ and $Ni$ up to 15 GPa [34–38]. In these MAC experiments a sudden drop ($\sim 20-40\%$) of $\kappa$ at the melting temperatures were observed and molten metals showed a constant resistivity over their experimental pressure scale. Studies carried out using LHDAC with pulsed laser, Konopkova et al. reported a low value of thermal conductivity of $Fe$ about $35 \text{ W m}^{-1}\text{K}^{-1}$ at 48 GPa and 2000 K, and in the range $18 - 44 \text{ W m}^{-1}\text{K}^{-1}$ from 48 GPa to 130 GPa and temperature range 2000 -3000 K, respectively [32]. In their previous work they estimated a value around $32 \pm 7 \text{ W m}^{-1}\text{K}^{-1}$ at 78 GPa and 2000 K using continuous wave (CW)
high power infrared laser, and finite-element numerical simulations\cite{31}. Very recently, a direct measurement reported $\kappa$ to be $70\text{-}80 \, W \, m^{-1} \, K^{-1}$ (with an uncertainty of 40\%) which remains constant in the hcp phase of Fe\cite{33}. In this study the temperature gradient across the sample surface was measured during heating the sample with a continuous wave infrared laser followed by computing the temperature gradient profile using COMSOL software under the steady state heat flow condition. The same study predicted that the effect of high temperature combined with melting of the sample will reduce $\kappa$ value to $40 \pm 16 \, W \, m^{-1} \, K^{-1}$ at the outer core conditions of Earth. The direct measurements of $\kappa$ during the melting of any Earth’s core materials have not been reported so far.

In the present work, we have carried out the measurements of thermal conductivity of Fe and Ni at high pressures using a single sided LHDAC facility and COMSOL software. The steady state heat flow condition is assumed in the COMSOL software and heat absorbed by the metal foil is calculated using thermodynamical equation. Temperature dependent thermal conductivity of compressed Fe and Ni at various pressure points are measured and compared with the literature values to see any changes in their values during melting. The pressure dependence melting temperatures estimated from the observation of the $\kappa$ value anomalies, and are compared with the literature.

II. EXPERIMENTAL AND METHOD

Thermal conductivity measurements at high-pressures are carried out by measuring temperatures across the sample in LHDAC and simulating the temperature gradient profile using COMSOL software\cite{40}. The LHDAC consists of a plate type DAC (Almax-Boehler design), and a diode-pumped Ytterbium fiber optic laser (YLR100-SM-AC-Y11) with central emission wavelength, $\lambda = 1.070 \, \mu m$ (maximum power 100 W). In this study diamond anvils of culet flat 300 $\mu m$ are used. T301 stainless steel gasket of initial thickness 225 $\mu m$ is preindented to a thickness of 50 $\mu m$ by compressing inside DAC. For containing the sample, and pressure transmitting medium (PTM) a hole of diameter $\sim 110 \, \mu m$ is drilled at the center of the culet impression with the help of electric discharge machine. Thin plates of Fe, and Ni of approximate thickness of about 15 $\mu m$ are made by compacting polycrystalline Fe, and Ni powders using a 300 ton hydraulic press operating at a pressure about 1.5 GPa. The same procedure is followed for the preparation of NaCl plate of approximate thickness
of about 12 µm, which is placed on the both sides of the metal plates. The metal plates (Fe/Ni), and the NaCl discs are kept at a temperature of 393 K in an electric oven for six hours to remove any trace of moisture. NaCl plates act as both PTM and thermal insulation to the sample from the diamond culet. Thin pieces of NaCl, and Fe/Ni-plates of desired size (approximate diameter of about 90-110 µm) are cut to load in the LHDAC. The sample is sandwiched in between NaCl inside the central hole of the gasket. A few ruby chips (approximate sizes of about 3-4 µm) are placed at the edge of the metal plates. Pressure inside the LHDAC before and after heating is determined from the shift of the ruby $R_1$ fluorescence lines\[41\]. For reporting the average value of the pressure is taken. Heating is carried out using the diode-pumped Ytterbium fiber optic laser. Heating geometry and procedure are similar to that described by Saha et al.\[33\]. Temperature of the sample surface is measured by spectraradiometry technique by fitting the Planck’s radiation function\[42\] in the wavelength range 650-900 nm \[43–45\]. Temperature of the hotspot can be estimated within an error of about ±15 K in this study and as described in other previous studies\[33, 45\]. However, for determination of actual temperature error in DAC during melting, Saha et al.\[45\] carried out measurements of melting temperatures of compressed argon within the error of ±25 K. Therefore, we attribute error in our temperature estimation to be within 50 K.

Temperatures at different positions are measured by translating the 50µm pin-hole attached to the spectrometer across the magnified image of the sample surface with a resolution of 1 µm. The sample is heated either at its center or one of its edge. We wait for about 5 – 10 minutes to have a constant temperature across the hotspot (focused heating laser beam area) is observed. We have carried out time dependent temperature measurements at hotspot and other position of the sample surface at a few pressure points for both metals. Fig.1 shows the time evolution of temperature at the hotspot and at a position $r_2$ away from the hotspot ($\sim 70$ µm) at two pressure points for Ni. Temperatures at same position with time are found to remain constant within the error limit and this ensures the steady-state condition. We start with a model that simulates the steady-state temperature distribution in a cylindrical metal plate continuously heated by a heat source. The equation that the heat conduction in system will follow is:

$$\nabla.(-\kappa\nabla T) = f(r)$$  \hspace{1cm} (1)

where, $\kappa$ is thermal conductivity of the material; $\nabla T$ is the temperature gradient across
the sample surface. We have used the boundary conditions for calculation of thermal conductivity of Fe/Ni metal in COMSOL and $f(r)$ is the heat source distribution given by:

$$f(r) = Q, \quad r \leq r_1; \quad T = T_g \text{ at gasket boundary}$$

(2)

Where $r_1$ is the radius of the hotspot, and $T_g$ is the temperature at the gasket boundary. The heat energy $Q$ absorbed by the Fe/Ni plate is calculated by

$$Q = mC_p(T_{\text{hotspot}} - T_{\text{room}})$$

(3)

where, $m$ is the mass of the sample contained at the hotspot, $C_p$ is the specific heat capacity of Fe/Ni at constant pressure, $(T_{\text{hotspot}} - T_{\text{room}})$ is the temperature difference between hotspot and room temperature, and $\nu$ is the modulation frequency (50 kHz) of the 1.070 $\mu$m wavelength laser. Exposure time of collected spectrum for temperature measurement is about 100 msec, which is much larger than the modulation period. The specific heat $c_p$ is taken to be 450 J/kg$^{-1}$K$^{-1}$ [33, 46, 47], and 420 J/kg$^{-1}$K$^{-1}$ [48] for Fe and Ni, respectively in our experimental pressure range.

Mass of the sample contained at hotspot $m$ in the Eqn. 3 is calculated as

$$m = \pi r_1^2 h \rho$$

(4)

where, $h$ is the thickness of Fe/Ni plate before loading and $\rho$ is the density of the Fe/Ni plate. Initial density of the Fe/Ni plate is determined from the weight of the cold compressed plate and measuring its dimensions, which agrees within 95% with that of a foil. All the used parameter values are listed in the Table-I. As the sample is contained inside the gasket and there is a negligible change in diameter of the gasket hole, mass of the sample at the hotspot is assumed to remain constant. We find 25% error in the absorbed power by considering errors in temperature measurement, dimensions of the plate (during mass measurement), and measurement of the hotspot diameter. By taking into account of the errors in every step, we find an uncertainty of about 30% in determination of thermal conductivity values in Fe/Ni plate (Table-II).

We have used finite-element software COMSOL Multiphysics to simulate the temperature distribution in the LHDAC. During the temperature measurements the hotspot along
with the sample is covered by PTM around all sides and inside the gasket hole. Three dimensional geometry of the sample chamber and an example of temperature distribution across compressed Ni plate are shown in the Fig.2. Simulation of temperature gradient is carried out to match the experimental temperature profile by varying the thermal conductivity of the sample.

III. RESULTS AND DISCUSSION

In Fig.3, we have shown the temperature gradient across the Ni plate at three different pressure points (8.7, 17.2, and 22 GPa). Temperature measurements are carried out during heating the sample at the center, which is shown in the right top corner inset (b). The central reddish glow is the hotspot with a temperature 1563 K at 17.2 GPa. On both side of the hotspot, temperatures are measured by translating the spectrometer pinhole with an step size 10$\mu$m. A photograph of the pinhole during measurement is shown in the inset (a) of Fig.3. The filled scattered symbols are the measured temperature, while the solid lines are the computed temperature profile. Thermal conductivity, density values of NaCl and all other geometrical values are given in Table-I. To match temperature gradient with experimental data points, we vary $\kappa$ of Ni plate. An excellent match is seen in the figure. Obtained $\kappa$ values at different pressures and temperatures of the hotspot are indicated in the figure.

In the rest of the measurements we have heated the Fe/Ni plate at one of their edge. We have measured $\kappa$ values of compressed Fe plate in its $\gamma$-phase, and the temperature of the hotspot is increased slowly beyond melting temperature following the phase diagram[51, 52] to see the effect of melting on $\kappa$ values. Temperature dependence of $\kappa$ values of Fe-plate at different pressures are shown in Fig.4. Our 8.5 GPa data is compared with that of Saha et al.[33] at 10 GPa in Fig.4(a). Both data show a decrease with temperature followed by another sharp decrease after a certain temperature. In Fig.4(c), we have compared the estimated $\kappa$ values with that at 1700 K from Saha et al., and at 1250 K from Deng et al.[33, 34] at 7 GPa. Data from Deng et al. are calculated from the resistivity data by using Wiedemann-Franz law ($\kappa = LT/\rho$; where $\kappa$, L, and $\rho$ are thermal conductivity in $W/m.K$, Lorenz number having value $2.44 \times 10^{-8}$ $W\Omega K^{-2}$, and electrical resistivity in $\Omega - m$, respectively)[34]. It is evident from the Fig.4(c) that the $\kappa$ values in this study
are consistent with the previous direct measurements\textsuperscript{[33]} and seem to agree very well with the indirect measurements of Deng \textit{et al.}\textsuperscript{[34]}. Also, it can be noted from the Fig.4 that the $\kappa$ values decrease with temperature and are consistent with previous studies\textsuperscript{[32, 33]}. Interestingly, we observe a sudden drop in the $\kappa$ values at certain temperatures at different pressures as shown in the figure. Sharp drops at 5, 7, and 8.5 GPa in $\kappa$ values are observed at temperatures $\sim$ 1975 K, 2035 K, and 2098 K, respectively and are attributed to the melting of the sample at the hotspot while the it is still at solid state at the edge opposite to the hotspot\textsuperscript{[51, 52]}. These sharp drop in the thermal conductivity values with respect to temperature are due to the presence of the liquid and solid interface at the boundary of the hotspot. Analogous to this study a sudden jump in the electrical resistivity values were also observed during melting of $Fe$ in high pressure electrical measurements\textsuperscript{[30, 34, 37, 39]}. At all the pressure points, we find 25-30% decrement in the thermal conductivity values of $Fe$-plate during melting at hotspot.

In Fig.5, we have compared temperature dependent $\kappa$-values of $Ni$ at different pressure points with the electronic thermal conductivity reported in an indirect measurements\textsuperscript{[36]} (resistivity) at 4, and 9 GPa in 3000 t MA large volume press. In their study resistivity data were converted to $\kappa$ values by using Wiedemann-Franz law and the Sommerfeld value of the Lorenz number. One can see from the figure that at each pressure the $k$ values show sharp decrease by about 30-35% at certain temperatures. Sharp decrease of $\sim$40% is observed by Silber \textit{et al.}\textsuperscript{[36]} during melting of the $Fe$ sample. Similar behaviour in the $\kappa$-values are also observed in the case of $Fe$ during melting at the hotspot in this study and previous direct measurements\textsuperscript{[33]}. Hence we attribute this phenomena to the melting of the sample at the hotspot. A larger drop ($\sim$ 5-10%) for $Ni$ with respect to $Fe$ in this study may be due to the higher density of $Ni$. Loss of long range ordering in the molten sample as well as the liquid-solid boundary in our case impede the heat conduction in the sample which in turn result in the low value of thermal conductivity.

The relative change in the thermal conductivity value of $Fe$ with respect to that at 5 GPa are shown in Fig.6(a) while the sample is at molten state at the hotspot area. The ratio shows a constant value of unity demonstrating the invariance of $\kappa$ along the melting boundary. Analogous to this observation, Silber \textit{et al.}\textsuperscript{[37]} found the constant value of electrical resistivity value in the pressure range 5 to 11 GPa in a MAC and Ohta \textit{et al.}\textsuperscript{[30]} in a DAC at 26 GPa for the molten $Fe$. In Fig.6(b), we have plotted $\kappa_P/\kappa_0$ (where $\kappa_0$ is
thermal conductivity of Ni at ambient pressure calculated from resistivity data of Chu and Chi [55] with pressure during melting of Ni-plate and compared with the data of of Silber et al. [36]. In our case the ratio is found to have a constant value around 1.15 and is observed to be about 15% higher with respect to that of Silber et al. [36]. Interestingly the ratios are found to remain constant with respect to pressure for both Fe and Ni along the melting boundary. The low thermal conductivity observed in the MAC experiments may result from high resistivity due to diffusion of W or Re from the thermocouple during melting of the sample [36, 37] as can be seen from Fig.6(b) in their study. It was reported that the liquid Fe maintain a local closed-packed hard-sphere structure and it remains invariant along its melting curve [63]. Silber et al. [36] discussed about having a P-invariant Fermi surface and constant electron mean free path at the onset of melting in Ni. This may be a reasonable explanation for observing the constant value of thermal conductivity of Fe and Ni along its melting curve, because both are transition metals having unfilled 3d cell and similar electronic configuration. In the other study of the resistivity measurements on Ni, a decrease in the resistivity during melting was observed [36] in a pressure range is from 0 to 9 GPa. Similar to the above phenomena, we have also observed a linear increase in the $\kappa$-values of Ni with pressure while they are plotted in a near isotherm (Fig.6(d)). Similar increase is also observed in case of Fe, which is shown in Fig.6(c) consistent with our previous study [33].

Cu has filled d cell, shows much steeper melting curve with respect to unfilled d cell containing materials such as Fe and Ni [60, 61, 67]. Fe and Ni has similarities in the magnetic states and it has been observed that alloying of Ni with Fe at 5.5% remains in the same hcp structure at high pressure and this structure is more stable than pure Fe [64, 65]. Also in ab initio calculations, the seismic properties of Fe and Ni alloy are observed to be almost indistinguishable from those of pure Fe [26, 66]. Due to the above mentioned similar properties, both Fe and Ni exhibit anomalous shallow melting curve [60] attributed to their d-electrons by Japel et al. From the sudden decrease in the $\kappa$-values we have calculated the melting temperatures at high pressures for Fe and Ni since at those temperature points there are no other structural or magnetic transitions. We have compared our measured melting temperature of Fe and Ni in Fig.7(a) and (b), respectively with those with literature values. Melting temperatures of Fe are found to have a very good agreement with the laser heated diamond anvil cell data [51, 58] and with the later work by Strong et al. [57]. This melting curve is observed to deviate by a very little amount with respect to the
previous work by Strong [56] and the multi-anvil experiments by Silber et al. [37]. For nickel, melting curve is found to be in very good agreement with all other laser heated and multi-anvil cell experiments [36, 59-61] except that reported by Lazor et al. [62]. Slight difference in the melting curve with Lazor et al. may be due to the different fitting procedures for the temperature measurements [62]. We fit the Planck’s radiation function in the wavelength range 650 nm - 900 nm taking constant emissivity with respect to wavelength, while Lazor et al. fitted by a least squares method to Wien’s approximation of Planck’s radiation function. It is predicted that the energy of the liquid state at the onset of melting occurs due to the partially filled d-shells and it leads to a loss of d-band structural periodicity as compared to filled d-band metals [60, 67]. It results in anomalies in compressibility and internal pressure in liquid Fe and Ni [68]. Hence all the above facts play important role in the observed shallow melting curve with pressure for partially filled d-shell metals.

The liquid outer core of the Mercury generates a weak dynamo like Earth [69] and it consists of molten Fe. The pressure and the temperature ranges of the Mercury core mantle boundary is considered to be in the range 5 to 8 GPa and 1850-2200 K. Our experimental pressure and temperature ranges for Fe belong to same range and we find that Fe has a thermal conductivity value of 60-70±20 Wm⁻¹K⁻¹ at their melting and it remains constant over the pressure range we studied. Apart from that we find thermal conductivity of Ni at melting in the range 65-70±20 Wm⁻¹K⁻¹ and it remains constant over the pressure range 4-22 GPa. Since the interior of the planets may have alloys of Fe and Ni, the constant behaviour of thermal conductivity values during melting put an important constrain over the heat conduction of the planetary interiors, specially planets like Mercury and Mars. Though more experiments and theoretical calculations are needed on the Fe, and its alloys.

IV. CONCLUSION

We have carried out the direct measurements of the thermal conductivity (κ) of Fe and Ni along its melting curve. Near-isothermal κ’s are observed to increase with pressure in both the metals due to the increase of density of the pressed metals. A sudden decrease of κ with temperature is observed for both the metals, and these temperatures for different pressures are attributed to the melting of the respective metals. Melting curve for both the metals are found to agrees very well with the other multi-anvil and laser heated experiments. Thermal
conductivity values for both the metals at their melt are observed to remain constant with
pressure in consistent with the other multi-anvil measurements. Constant values of $\kappa$ in these
metals during melting at different pressures can be attributed due to the constant Fermi
surface and an invariant electron mean free path in melt for both the metals. Melting gives
rise to loss of long range order and maintains a local closed-packed hard-sphere structure,
which remains invariant along its melting curve resulting in an independent movement of
atomic metals. The above phenomena is observed in the unfilled d-band transition metals.

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All authors has equal contribution. Both authors reviewed the manuscript.

V. ADDITIONAL INFORMATION

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Table I. The parameter values used in COMSOL for determination of the thermal conductivity of Fe and Ni.

| Material        | Dimensions | Density (Kg.m$^{-3}$) | Thermal Conductivity ($\kappa$) (W m$^{-1}$K$^{-1}$) |
|-----------------|------------|-----------------------|-----------------------------------------------------|
| Fe              | 15, and 90-110 | 7620          | Variable                                            |
| Ni              | 15, and 100-120 | 8485     | Variable                                            |
| NaCl            | 12, and 110-120 | 2160          | 6 [49]                                              |
| Gasket (Steel)  | 40-45, and 10$^6$ | 8050       | 20 [50]                                              |

Table II. Detailed error analysis in the measurement of the thermal conductivity of Ni plate at a pressure of 17.2 GPa. The radius of hotspot is $r_1$, the ambient thickness of the Ni plate is $h$, mass of the hotspot is defined as $m$, specific heat of Ni is $c$. $T_1$ is the temperature of the hotspot, $T_2$ is the temperature at a distance $r_2$ from the center of hotspot, $Q$ is the absorbed power at hotspot measured using Eqn.4, and $k$ is thermal conductivity measured using Eqn.3. The error in $r_1$ is assigned from the difference of the half of beam waist of the incident infra-red laser and the radius of the hotspot. The error in determination of the thickness ($h$) of the compressed Ni-plate is calculated from the several measurements of thickness before loading the sample. The error in mass ($m$) of the hotspot is measured from the error measurements of density and volume of the hotspot assuming the quasi-hydrostatic condition. The error in $C_p$ is assigned from the literature [48]. The error in $T_1$ and $T_2$ is already explained above and is taken to be 50 K. The error in $Q$ is assigned from the propagation of the errors. The error in $r_2$ is assigned from the resolution of the motion of spectrometer pinhole. The error in $k$ is assigned from all the propagated errors. A total error is estimated to be 30% in the thermal conductivity values.

| $r_1$  | $h$  | $m$  | $C_p$  | $T_1$ | $T_2$ | $Q$  | $r_2$ | $k$  |
|--------|------|------|--------|-------|-------|------|-------|------|
| $\mu$m | $\mu$m | Kg   | JKg$^{-1}$K$^{-1}$ | K   | K   | Watt | $\mu$m | Wm$^{-1}$K$^{-1}$ |
| Measured | 9    | 15   | 6.2$\times$10$^{-11}$ | 420 | 1740 | 1467 | 1.9   | 70   | 103   |
| Error  | ±2   | ±0.2 | ±1.4$\times$10$^{-11}$ | ±5  | ±50  | ±50  | ±0.5  | ±1   | ±31   |
Figure 1. Time dependent temperatures at the hotspot (filled symbols) and at a distance $r_2$ (70 µm) from the hotspot (open symbols) on a $Ni$ plate at two pressure points while heated at different temperatures.
Figure 2.  (a) Schematic cross sectional view of the sample chamber with gasket during heating of Ni plate at one of its edge. (b) Schematic drawing of the sample chamber geometry inside the gasket hole of the LHDAC having 300 micron culet in a COMSOL software. Number 1 represents the hotspot at the one of edge of the Ni plate, 2 represents the compressed Ni plate, and 3 represents pressure transmitting medium (PTM). (c) Cross sectional view of computed temperature distribution in the sample chamber and gasket material while the hotspot temperature is 1740 K and Ni thermal conductivity is 103 Wm⁻¹K⁻¹. (d) Computed line profile of the temperature on the Ni plate for the above condition.
Figure 3. Measured and computed temperature distribution on the Ni plate heated at different pressures. Temperatures were measured by translating the 50 µm pinhole attached to the spectrometer across the magnified image (magnified by 16 times) of the sample surface. Inset (a) Shows the magnified image of the 50 µm pinhole while heating the Ni plate. Pinhole captures thermal radiation of 3 µm of the sample surface and (b) shows the magnified image of the Ni loaded sample chamber at a pressure 17.2 GPa heated at 1563 K under transmitting light. The redish glow in both the inset is the hotspot about diameter 18 µm.
Figure 4. The comparison of temperature dependent thermal conductivity of Fe at different pressures. (a) Represents the data of Saha et al. [33] at a pressure 10 GPa. (b), (c), and (d) Represents the data obtained in this work at 5, 7, and 8.5 GPa respectively. In (c), green open circle and blue open triangle data are from electrical resistivity measurements by Dang et al. [34] and direct measurements using LHDAC by Saha et al. [33] around 7 GPa, respectively. At each pressure, after certain temperature, $\kappa$ shows a sudden drop. These transition temperature values are in well agreement with the melting points of Fe at the respective pressures. [51, 52]
Figure 5. The comparison of temperature dependent thermal conductivity of Ni at different pressures. In (a), and (b) all filled red circles represent our data at 4, and 8.7 GPa, respectively while green open circles represent the data by Silber et al.\cite{36} from electrical resistivity measurements in a MA large volume press at 4 and 9 GPa. In both data in (a), and (b) $\kappa$ show a sharp fall after certain temperature and reported to be melting\cite{36}. (c), (d) Represent temperature dependent $\kappa$ of Ni in our study at 17.2 and 22 GPa. Melting induced sharp fall in $\kappa$ is evident in (c), and (d).
Figure 6.  
(a) The ratio of pressure dependent $\kappa_P$ to that at 5 GPa $\kappa_5$ of Fe during melting at hotspot shows a constant value. Filled circles represent our data and open circle represent data of Saha et al.\cite{33}.  
(b) Comparison of ratio of pressure dependent $\kappa_P$ to that at ambient pressure $\kappa_0$ of Ni during melting. Filled circles represent our data and open squares represent data of Silber et al.\cite{36}. Both data shows a constant value of these ratio. Errors in our data are assigned from the deviation of $\kappa$ values during melting at the respective pressures.  
(c), (d) Represent the pressure dependent near isothermal thermal conductivity of Fe, and Ni, respectively. All the filled symbols represent our data while all the open symbols are the literature values of $\kappa$\cite{33}.  

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Figure 7. Comparison of the melting temperature with pressure estimated from the observation of sharp fall in the $\kappa$’s values with the other measurements [36, 37, 51, 56–62]: (a) Fe, (b) Ni, respectively. All the filled symbols represent our data while all the open symbols are the reported data [36, 37, 51, 56–62] using different techniques.