A E J (2022) 61, 12111 12122

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Alexandria Engineering Journal

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# Synthesis, characterization and thermal conductivity of water based graphene oxide–silicon hybrid nanofluids: An experimental approach

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18 A 2022; 1 J 2022; 6 J 2022

**KEYWORDS**

G - ;
1 ;
C

**Abstract** H 1
. I , -
. 1 , (G )-
( )/ . 1
1
. 25 50 °C
5 °C. I
. A
,
.



## 1. Introduction

I , (G ),
,
1 1,2 ,
3,4 , 5 , 6,7 , 8,9 . G -
-
,
( ℃) ( ,
- , )
G G
G - 1 10 , G + 1 2 11 , G + C 12 , G + A 2-
3 13,14 , G + 2 15 , G + C 16 18 , G +
19 , G - 20 .
. 11 ℃
G + 1 2/
(20 50 °C) (0.05 1.0
%). 1
℃ 32.8% 50 °C 1 %.

* C .
E- : . @ . (G. H ).
F E , A
.

:// . /10.1016/ . .2022.06.012

**Nomenclature**

1 , /( K)
1 , K
, -

*Greek symbols*
$\phi$ , -.
$\varphi$ , -

*Subscripts:*

. 12 G - C
C. F
- . 1
C ,
33.2% 50 °C
1 %.
G . 13 C
G A 2 3
(50%-50%). 1 (
, , H, ,
) C
. C
0
70 °C 0.025 0.20 %. B D
0.2 % G A 2 3 (1:1), C
7.2%
0 °C. ,
C -
(1.76%).
A , 1 1 . 14
C G A 2 3
. 1 C
(0.1, 0.25, 0.5, 0.75, 1%) 25
50 °C. A , C
33.9% 1.0%
50 °C.
. 15 C G
2/ . 1
0.05 1.0%
25 50 °C. 1
C 26.93%, 50 °C 1.0% .
. 16 , C C -
G / ( ) + (EG) (0.5:0.5)
, 25 50 °C
0.1 1.6%. 1
C
. F 1.6%, C
43%.
I , . 17 C
G -C / -EG
- . 1
C , 1
.
. 18
G -C /
. I C
-
,
1.046 / K 0.03 %
33 °C.
1 19 C
-G
(0.8 0.2). 1
20 60 °C -
0.025 0.2%. 1
C 8.8%, -
60 °C 0.2% .
. 20 C
/ G ( G )- -
,
- . B ,
C 0.1% -
50 °C.
I , C . 21
/ G - 2
G - 2 . 1 -
940
7510. 1
0.01, 0.05, 0.07 0.1 % (30
50 °C). 1 C -
. 1 C
102.97% 0.07 % , 1:7 ,
40 °C.
1 - G -A 2 3 -
/
. 22 . 1 C 2.076 / K
0.1 % 45 °C, -
( ).
D ( E-C D,
C D)
. B
- .
I ,
, ,
- - . I , -
, , ,
, C - -
. I , G
H . E -
. A , DL
-
. 1 G - /
0.25% -
, 20% G -80% , 40% G -60% , 50%

G -50% , 20% 6 -40% 80% G -20% . I - ℃ - , ℃ G - / ( ℃ ) - . A , 1 20 50 °C. F , / ℃. .

## 2. Equations for computing the effective thermal conductivity

1 , . 1 26 ℃ . I ( ), - 1 1 F . 1. 1 A - H4

## 3. Experimental procedure

### 3.1. Synthesis of silicon nanoparticles (Si NPs)

**Table 1** E .

| | | B | | C | C |
|---|---|---|---|---|---|
| . 23 | 2019 | | G | 0.05 1.5 % 20 60 °C | $\frac{k_{nf}}{k_{bf}} = 0.998 + 0.023 \cdot T^{0.669} \cdot \varphi^{0.678}$ |
| 1 . 24 | 2019 | | G | 1.0 4.5 / 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 0.863 + 0.0412 \cdot T^{0.41 \cdot \varphi^{0.224}}$ |
| 1 . 11 | 2020 | | G + 1 2 | 0.05 1.0 % 20 50 °C | $\frac{k_{hnf}}{k_{bf}} = 1.017 + 0.072 \cdot 1.029^{T} \cdot \phi^{0.773}$ $k_{bf} = 0.5642 \cdot e^{0.002748T}$ |
| K . 12 | 2019 | | G + C | 0.05 1.0 % 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 0.015229 \cdot T^{0.52876+0.31508 \cdot \phi} + 0.92124$ |
| G . 13 | 2020 | | G + A 2 3 | 0.025 0.2 % 0 70 °C | $k_{hnf} = 0.5705 + 9.041 \cdot \varphi + 0.001868 \cdot T + 1738 \cdot \varphi^2 - 0.09111 \cdot \varphi \cdot T - 7.805 \cdot 10^{-6} \cdot T^2$ |
| . 14 | 2019 | | G + A 2 3 | 0.1 1.0 % 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 0.0031 \cdot T^{1.185} \cdot \phi^{0.863} + 1.006$ |
| B . 15 | 2020 | | G + 2 | 0.05 1.0 % 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = \left(\frac{0.13658+\phi}{0.13965-0.00262 \cdot T}\right) - 7.20304 \cdot \phi$ |
| . 16 | 2019 | - (50%-50%) | G + C | 0.1 1.6 % 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 0.2051 \cdot \left(\frac{T}{T_0}\right)^{0.7803} \cdot \phi^{0.5059} + 0.9679 \qquad T_0 = 25°C$ |
| . 17 | 2021 | E (50%-50%) | G + C | 0.1 1.6 % 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 0.95283 - 0.03116 \cdot \left(\frac{T-T_L}{T_H-T_L}\right)^{1.37626} + 1.76648 \cdot \phi^{0.44} + 1.3481 \cdot \left(\frac{T-T_L}{T_H-T_L}\right)^{1.37626} \cdot \phi^{0.44} \qquad T_L = 25°C \quad T_H = 65°C$ |
| 1 19 | 2021 | (80%-20%) | G + | 0.02 0.4 % 20 60 °C | $\frac{k_{hnf}}{k_{bf}} = 0.534381 \cdot \left(\phi^{0.061895} + T^{0.038504}\right)$ $\frac{k_{hnf}}{k_{bf}} = 0.993126 + 0.676064 \cdot \phi + 0.001067 \cdot T - 1.661853 \cdot \phi^2 - 0.00000 \cdot T^2 + 0.000643 \cdot \phi \cdot T$ |
| . 18 | 2020 | | G + C | 0.01 0.03 % 30 42 °C | $k_{hnf} = 0.056 \cdot T + 1415.69 \cdot \phi - 1.252$ |
| A1 25 | 2021 | | G | 1.0 5.0 / 25 50 °C | $\frac{k_{hnf}}{k_{bf}} = 1 + 0.03655 \cdot \varphi^{0.90886} \cdot \left(\frac{T}{T_0}\right)^{1.02496}$ |
| . 20 | 2020 | | G + | 0.03 0.1 % 32 52 °C | $k_{hnf} = 1191.9249 \cdot \phi + 0.05688 \cdot T - 1.775$ |
| C . 21 | 2020 | | G + 2 | 0.01 0.07 % 25 50 °C | $k_{hnf} = -1.2362 + 0.05957 \cdot T + 426.2518 \cdot \phi$ |
| B . 22 | 2021 | | G + A 2 3 | 0.01 0.1 % 30 45 °C | $k_{hnf} = 502.6909 \cdot \phi + 0.08 \cdot T - 2.05$ |

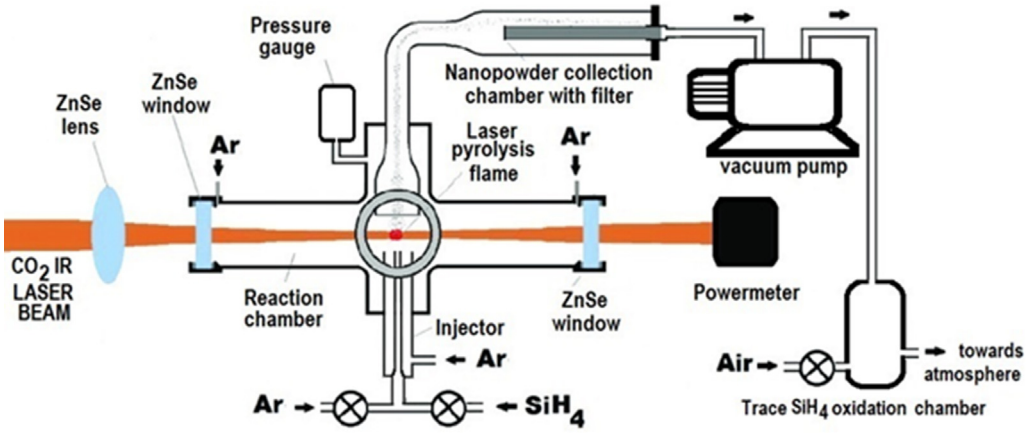



**Fig. 1** 1 -

( A )

I -

$H_4$ -

/ . 1

F . 1. 1 -

. F . 2

, . A , F . 2, :

) )

. 1

1 2.

*3.2. Synthesis of graphene oxide (GO)*

A G

1 ( 300 500 μ ). F

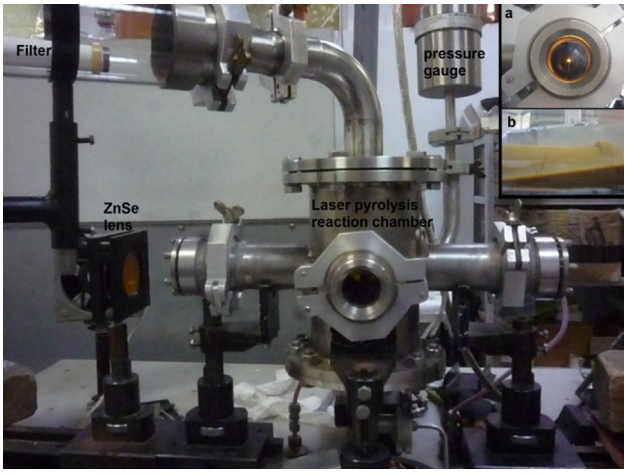



**Fig. 2** 1 .

H

A ( A ) 27 . B , 100 -

$H_2$ 4

4 4 10 12 K 4

4 . , 4 1

2

3

10 -

800 . 1

,1 35 °C

. A , -

, 20

. A ,

85 °C 15 ,

. 1

40 35% $H_2$ 2 ,

- . 1

300 4% HC , -

H . F ,

15% .

*3.3. Preparation of graphene oxide/silicon hybrid nanofluid*

I , G

: 0.5 / + 2 / G , 1 / + 1.5 / G , 1.25 / + 1.25 / G , 1.5 / + 1 / G 2 / + 0.5 / G , .

1 - - G

F . 3.

G - .

28 .

*3.4. Characterization and stability of graphene oxide/silicon hybrid nanofluid*

1 G

15 20 1 ,

(A 2 E ) 1 F , A,

. 1 - D

, D -

**Table 2** .

| E | D $_{H_4}$ | $D_A$ | $D_A$ | $D_A$ | | L L/A / L | F . °C . | C | I . |
|---|---|---|---|---|---|---|---|---|---|
| $H_4$ | 20 | 100 | 1500 | 200 | 250 | 350/335 | 600 | 0.9 | 12.5 |

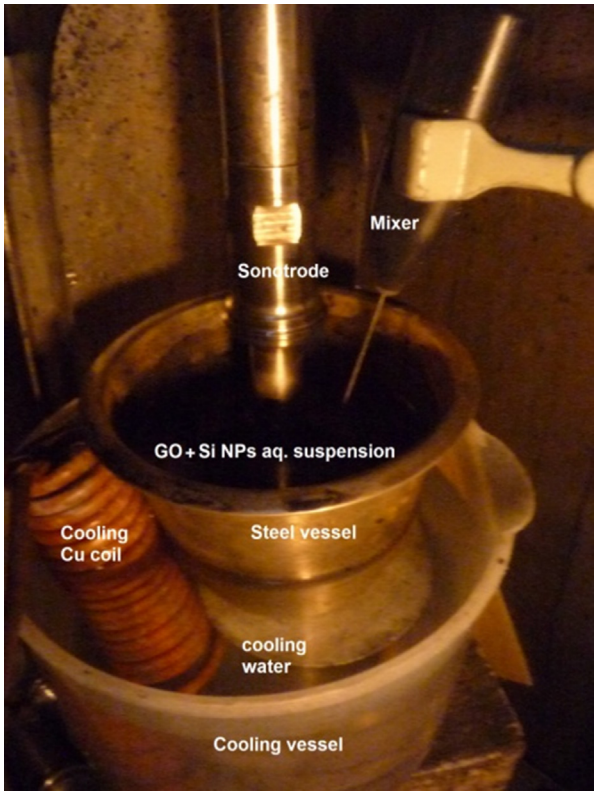



**Fig. 3** 1 - - G .

: 0.02° /20 - / , 2 (20° 100°) , 40 1 30 A. I , (λ = 0.15418 ). F ( ) H -100 532 - , 10 - 1 - .

*3.5. Thermal conductivity measurement*

I , ℃ G - / 20 50 °C KD2- (D , I ., A). D , (H 1 C10 5/ 0.04 °C - . I , -

1 , ℃ . 1 I 1 29 , 0.55% (F . 4). 1 . 1 15 .

## 4. Results and discussion

*4.1. Characterization and stability of graphene oxide/silicon hybrid nanofluid*

1 E F . 5. 1 15 50 / . 1 - (F . 6), 1 JC D .72 2111. D - , 20.7 . 1 E , . F . 7 E 5 / + 5 / G ( ), . A , G - .

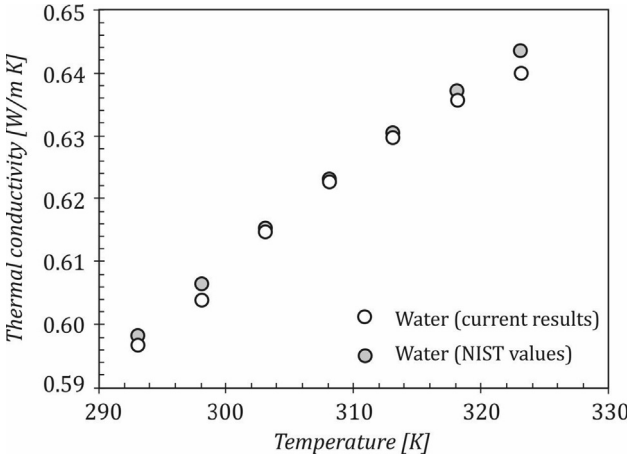



**Fig. 4** 1 .

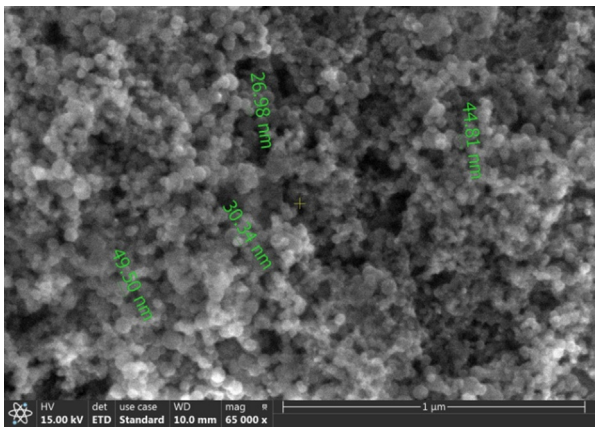



**Fig. 5** E .

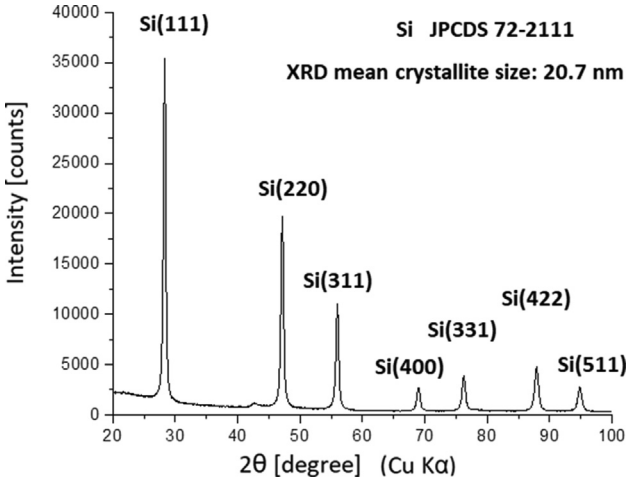



**Fig. 6** - .

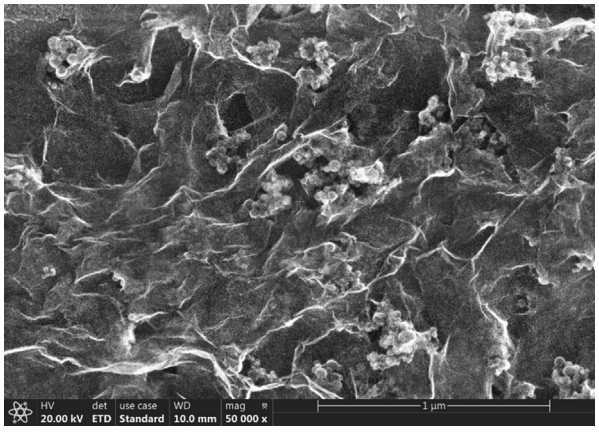



**Fig. 7** E G .

F . 8 DL . F G , - - , 1 100 , , 100 .

F . 9 . F G , - . 1 1 / G , . 1 $^{0.8}$G -$^{0.2}$ . 1 ; 6 .

### 4.2. Thermal conductivity

F . 10 C G - / 0.25% . 1 C G - C . A , F . 11 G ($^{0.8}$G :$^{0.2}$ ) C - ($^{0.2}$G :$^{0.8}$ ) . 1 - . I , , . 1 . C - , 30 . 1 - C G - / F . 12 ( - ). 1 C G . 1 C G - / . 1 C,

$$\left[\left(k_{hnf}-k_{bf}\right)/k_{bf}\right]\cdot 100,$$

- . 1 , 7.97% $^{0.8}$G :$^{0.2}$ 50°C. 1 - C - . A , , - , B . A , B - - , 31 . F . 13 C - G , , $^{0.8}$G :$^{0.2}$ . I G / C / . , G C. I 1 C - , , , - , , . 1 - : . / ( ) , B B 32 . - C - , ,

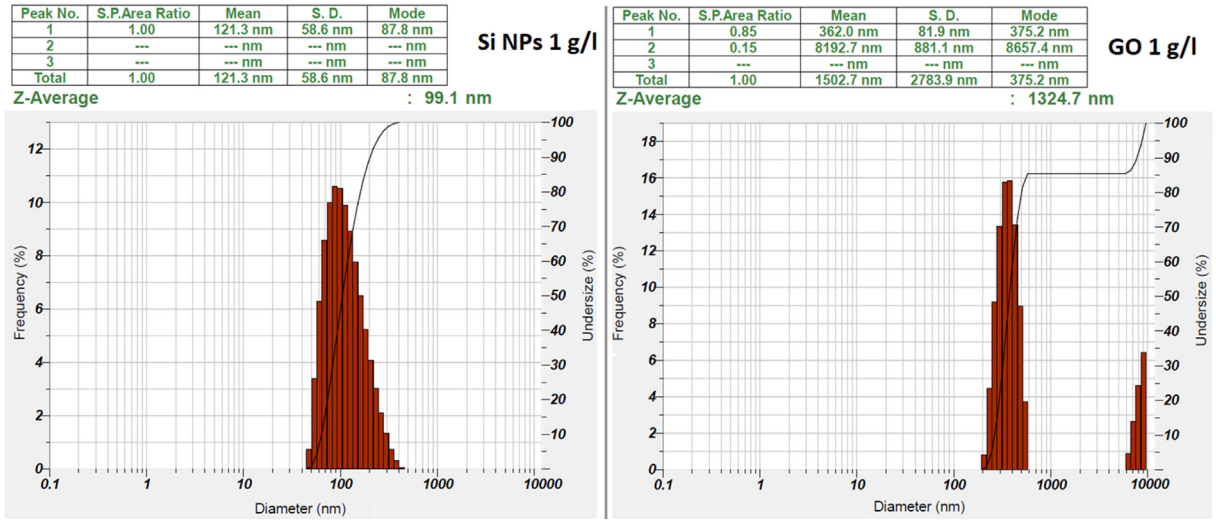



**Fig. 8** DL - ( : 1 / , : 1 / G ).

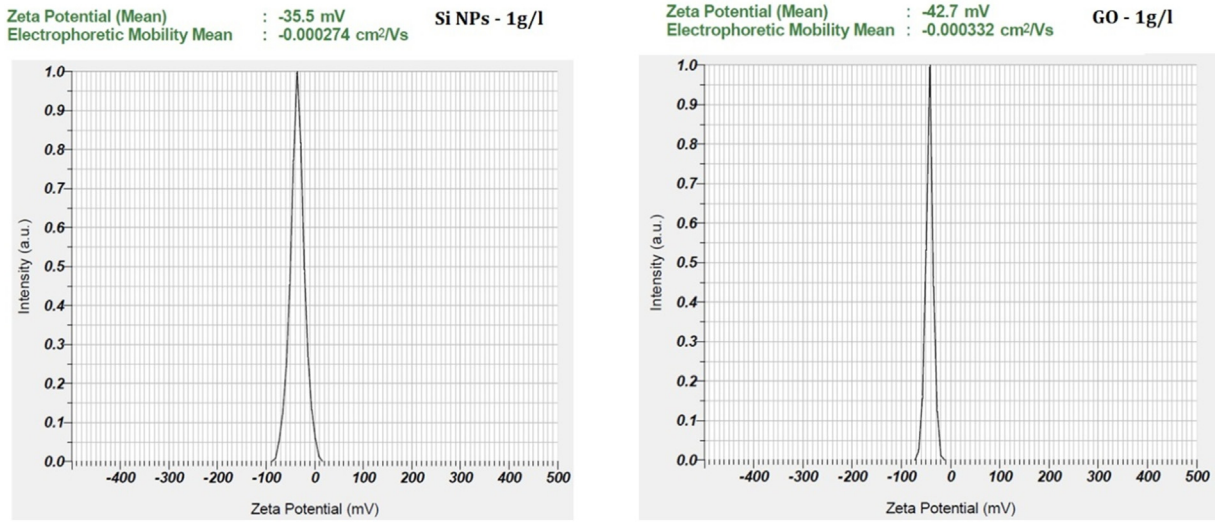



**Fig. 9** .

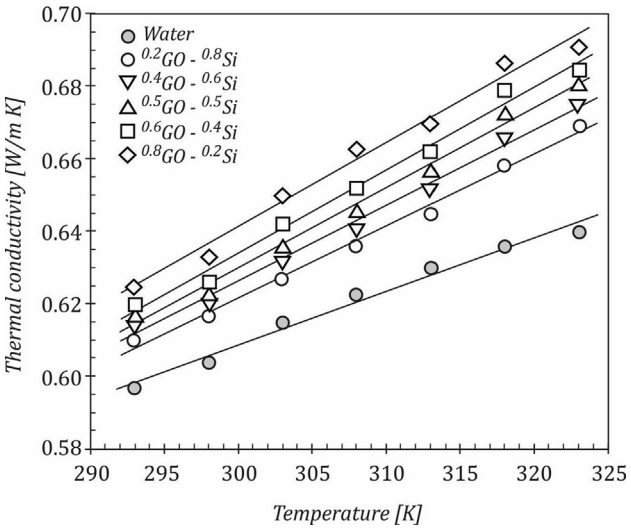



**Fig. 10** 1 .

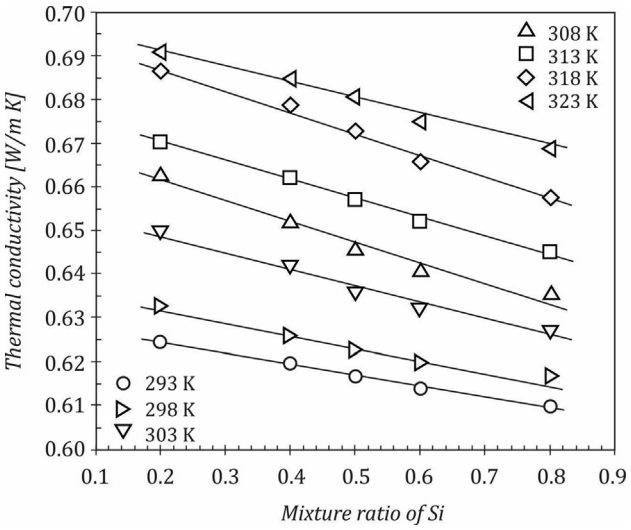
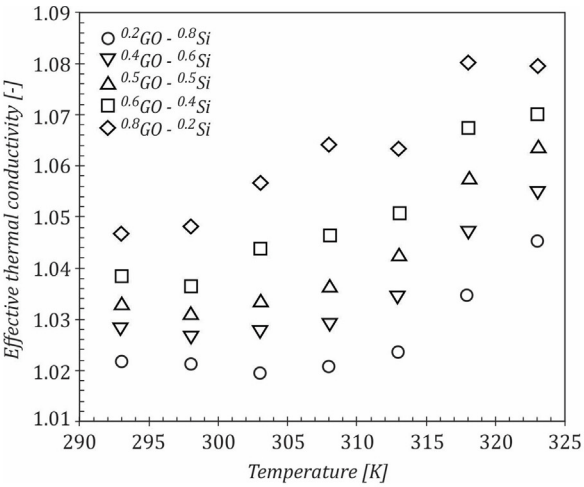


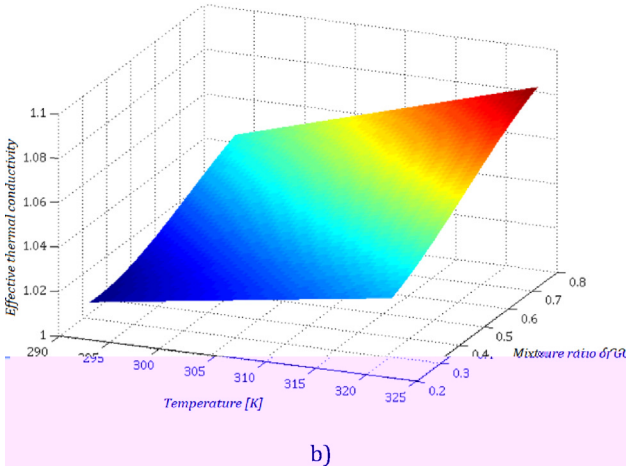

**Fig. 11** E G .

33 H 34 36 .

14 B C , B C . 1 G . 13 C . 37 38 . 1 - , . C / - - 39 40 . F . 14 ( - ) C - -




a)




b)

**Fig. 12** 1 C: ) , ) G (3D).

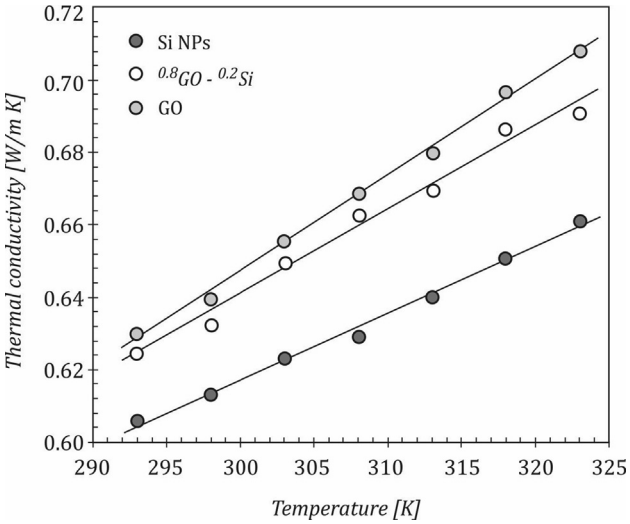
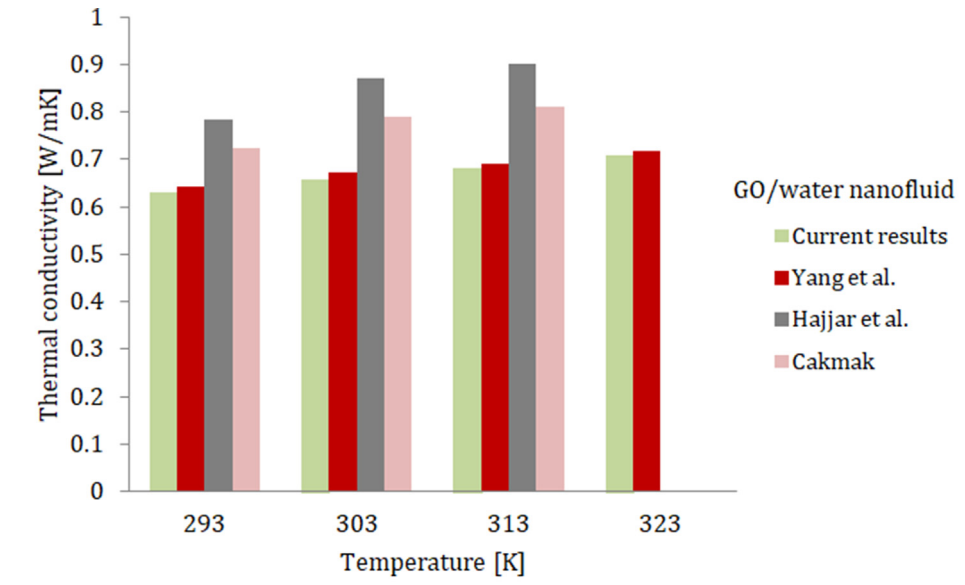
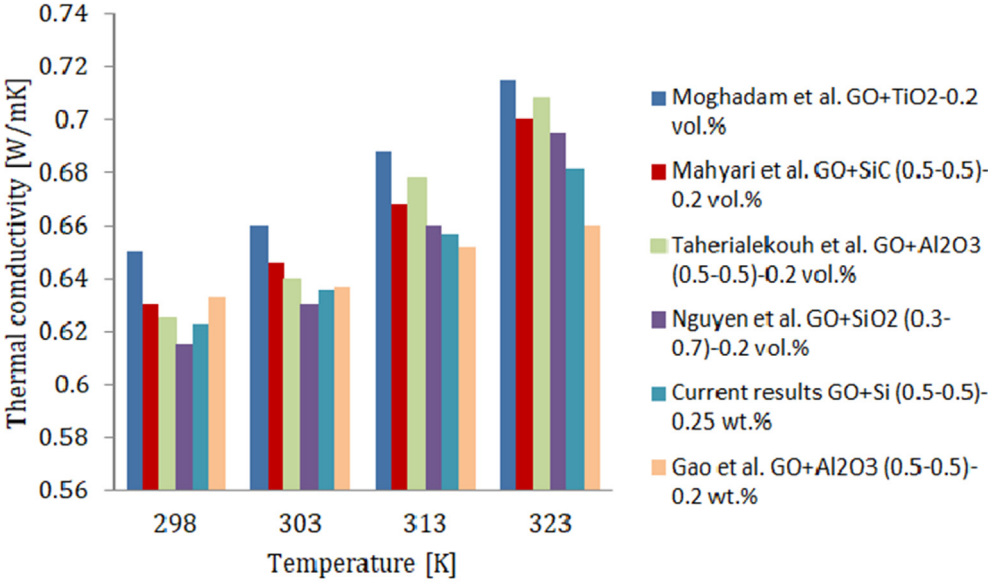



**Fig. 13** C .




a)




b)

**Fig. 14** 1 : ) G / 0.25 %; ) G .

. I , ℃ G / B , -
10.62% , ℃ . 1 -
G - / 293 323 K , *R*,
7.97% 0.8 0.2 323 K. C G :
G / ,
. 23 . 1

$$k_{eff} = \frac{k_{hnf}}{k_{bf}} = 0.6979 + 0.2793\left(\frac{T}{T_0}\right) + 0.006156 \cdot R \quad (1)$$

℃ 12% 0.25 % 323 K. -
$T_0 = 273K$ *R* G .
H . 41 C 1 1 42 . 1 ( - ) 1
℃ 47.54% 30.65% 0.9104 E ( E) 0.005253.
40 °C 0.25 %. 1 -
1 3 ℃ E . (1)
. F . 15

**Table 3** ¹ ℃ .

| | B | | C | E ℃ % / ℃ |
|---|---|---|---|---|
| . 43 | DI | G | 1.0 5.0 % 10 60 °C | 7.5%−30.2% 5.0 % |
| . 44 | DI | G | 0.01 0.1 % 23 40 °C | 10%−16% 40 °C |
| H . 41 | | G | 0.05 0.25 % 10 40 °C | 14.75% − 47.54% 40 °C |
| ¹ . 45 | | G | 0.01 0.1 % 25 55 °C | 1.03 1.32 45 °C |
| A 46 | DI | G | 0.005 0.02 % 30 70 °C | 24% 0.02 % 70 °C |
| . 47 | | G | 0.05 0.2 % 25 °C | 1.035 1.13 |
| ¹ . 48 | DI | G | 0.001 0.045 % 25 50 °C | 1.024 1.11 50 °C |
| E . 49 | DI | G | 0.01 0.5 % 25 60 °C | 8.8% − 55.2 % 60 °C |
| C . 50 | | G | 0.02 % 30 80 °C | 26.25% 80 °C |
| E L 51 | DI | G | 0.01 0.1 % 25 °C 40 °C | 8.33% − 23.33% 40 °C |
| . 52 | | G | 0.025 0.1 % - | 28% 0.1 % |
| . 5 | | G | 0.25 1.5 /L 25 °C | 1.62% − 5.38% 25 °C |
| C¹ ¹ 42 | DI | G | 0.01 0.25 % 20 40 °C | 4.84%-30.65% 40 °C |
| . 23 | | G | 0.05 1.5 % 20 60 °C | 4.0% − 48.15 % 60 °C |
| ¹ . 24 | | G | 1.0 4.5 / 25 50 °C | 25.27%, 4.5 / 50 °C |
| . 53 | | G + C 3 4 | 0.05 0.20 % 20 60 °C | 8.58%-9.14% 60 °C |
| ¹ . 11 | | G + ¹ 2 | 0.05 1.0 % 20 50 °C | 32.8% 1.0 % 50 °C |
| K . 12 | | G + C | 0.05 1.0 % 25 50 °C | 33.2% 1.0 % 50 °C |
| G . 13 | | G + A 2 3 | 0.025 0.2 % 0 70 °C | 7.1% 0.2 % 0 °C |
| . 14 | | G + A 2 3 | 0.1 1.0 % 25 50 °C | 15.7% 33.9% 50 °C |
| B . 15 | | G + 2 | 0.05 1.0 % 25 50 °C | 26.93% 1.0 % 50 °C |

.

## 5. Conclusions

I , . ¹
H
G .
F E , - - 0.25 % 5
, DL . - .
¹ -
G ¹ -
. A ℃ -
. ¹ - . , -
: -

- ¹
7.97% $^{0.8}$G :$^{0.2}$ 50 °C.
- ¹ G
.
- ¹
.
- A . ¹
25 °C 50 °C -

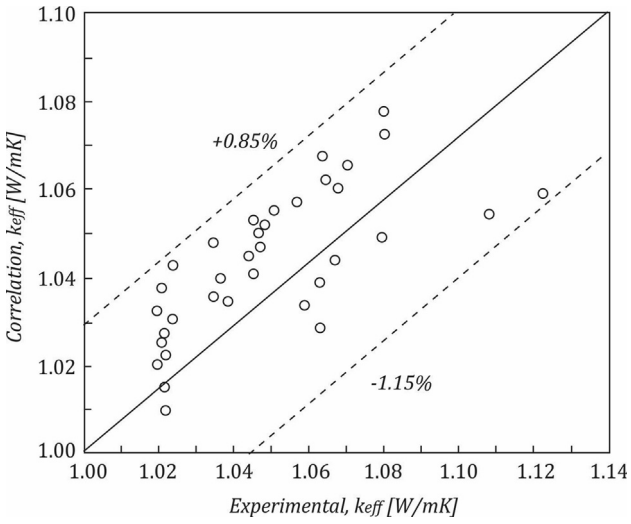



**Fig. 15** E . (1) .

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## Declaration of Competing Interest

## Acknowledgments

E , C C - FI CDI, -III- 4-ID- CE-2020-0353, -III- 2-2.1- E D-2019-4951/C 304 ED/2020, CDI III.

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