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Talebizadeh, P, Rahimzadeh, H, Babaie, M, Anaghizi, SJ, Ghomi, H, Ahmadi, G and Brown, R

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1 **Evaluation of Residence Time on Nitrogen Oxides** 2 **Removal in Non-thermal Plasma Reactor**

3
4 **Pouyan Talebizadeh¹, Hassan Rahimzadeh^{1,*}, Meisam Babaie², Saeed Javadi**
5 **Anaghizi³, Hamidreza Ghomi³, Goodarz Ahmadi⁴, Richard Brown⁵**

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7 **1** Department of Mechanical Engineering, Amirkabir University of Technology,
8 Tehran, Iran, **2** Petroleum and Gas Engineering Division, School of Computing,
9 Science and Engineering (CSE), University of Salford, Manchester, United
10 Kingdom, **3** Laser and Plasma Research Institute, University of Shahid Beheshti,
11 Tehran, Iran, **4** Department of Mechanical and Aeronautical Engineering, Clarkson
12 University, New York, United States, **5** Biofuel Engine Research Facility,
13 Queensland University of Technology, Queensland, Australia

14
15 * Corresponding author

16 E-mail: rahimzad@aut.ac.ir

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1 **Abstract**

2

3 Non-thermal plasma (NTP) has been introduced over the last few years as a
4 promising after- treatment system for nitrogen oxides and particulate matter removal
5 from diesel exhaust. NTP technology has not been commercialised as yet, due to its
6 high rate of energy consumption. Therefore, it is important to seek out new methods
7 to improve NTP performance. Residence time is a crucial parameter in engine
8 exhaust emissions treatment. In this paper, different electrode shapes are analysed
9 and the corresponding residence time and NO_x removal efficiency are studied. An
10 axisymmetric laminar model is used for obtaining residence time distribution
11 numerically using FLUENT software. If the mean residence time in a NTP plasma
12 reactor increases, there will be a corresponding increase in the reaction time and
13 consequently the pollutant removal efficiency increases. Three different screw
14 thread electrodes and a rod electrode are examined. The results show the advantage
15 of screw thread electrodes in comparison with the rod electrode. Furthermore,
16 between the screw thread electrodes, the electrode with the thread width of 1 mm
17 has the highest NO_x removal due to higher residence time and a greater number of
18 micro-discharges. The results show that the residence time of the screw thread
19 electrode with a thread width of 1 mm is 21% more than for the rod electrode.

1 **Keywords:** Non-thermal plasma; Residence time; Nitrogen oxides removal;
2 Electrode configuration; Specific energy density.

3 **Introduction**

4

5 Non-thermal plasma (NTP) technology is known as a reasonably new pollution
6 reduction method [1]. In the last two decades, significant developments have been
7 made in order to commercialise and utilise this technique in various pollutant
8 production systems [2]. NTP treatment of exhaust gases is effective for emission
9 reduction through introducing plasma inside the exhaust gases. Polluted exhaust gas
10 undergoes chemical changes when exposed to plasma. Eventually, oxidation
11 processes dominate in the plasma treatment of exhaust gas. These reactions include
12 oxidation of hydrocarbons, carbon monoxide, nitrogen oxides and particulate matter
13 [3]. Due to the increasing concerns for human health and more stringent emission
14 regulations, exhaust emission reduction has become a major issue in recent years.
15 Nitrogen oxides (NO_x) are considered as one of the major pollutants and toxic
16 gaseous emissions in the environment. The main sources of NO_x are vehicles (49%),
17 electric utilities (27%), industrial, commercial and residential sources (19%) and all
18 other fuels burner sources (5%) [1, 4]. Among the various types of NO_x , nitric oxide
19 (NO) and nitrogen dioxide (NO_2) are considered toxic, and the abbreviation NO_x
20 usually refers to the sum of NO and NO_2 in standards [1]. Around 95% of NO_x

1 emitted from incineration processes is NO and 5% is NO₂ [5]. NO is less poisonous
2 than NO₂. However, as for most radicals, NO reacts readily with oxygen through
3 photochemical oxidation due to the instability and forms of NO₂ [6]. Some of the
4 negative effects of NO_x are respiratory and cardiovascular diseases, nose and eye
5 irritation, mortality, visibility impairment, acid rain, global warming, the formation
6 of toxic products and water quality deterioration [1, 7-9].

7 NO_x removal from the exhaust gas in automobile and stationary engines has
8 been a serious challenge for researchers, as many conventional techniques such as
9 catalysis, exhaust gas recirculation and engine design modifications cannot always
10 meet expectations, especially given the introduction of increasingly stringent
11 regulations [10, 11]. In this context, the electrical discharge plasma technique
12 appears to be very promising [12]. There are several studies in literature that
13 examined NTP reactors in order to remove NO_x from exhaust gases [1, 10, 13-23].
14 However, efficient NO_x removal within an acceptable energy consumption range
15 has not been achieved thus far until now.

16 Residence time is an important parameter in different types of reactors which
17 characterizes the byproducts of the reactor outlet. In a reactor, the various atoms in
18 the feed spend different times inside the reactor. In other words, there is a residence
19 time distribution (RTD) of the material within the reactor. In any reactor, the
20 distribution of residence times can significantly affect its performance [24]. In

1 literature, there are several studies which investigate the effect of reactor residence
2 time to improve the chemical performance of the reactor [25-29].

3 In the NTP reactors, residence time is an important factor governing the
4 decomposition rates of different species in the exhaust gas [29, 30]. By increasing
5 the residence time, the polluted gases spend more time in a plasma state and the
6 chance of pollution reduction increases with the use of the NTP reactor [28]. Jogan
7 et al. [28] studied the effect of residence time on CO₂ removal from combustion
8 exhaust gases using a ferroelectric packed-bed reactor. They calculated the residence
9 time as the ratio of reactor volume times the void fraction to the volumetric flow
10 rate. The results showed that increasing the gas residence time results in a higher
11 CO₂ removal due to a decrease in the energy yield of CO₂ reduction. Futamura et al.
12 [31] studied the performance of three different plasma reactors i.e. ferroelectric
13 packed-bed (FPR), pulsed corona (PCR), and silent discharge (SDR) on the
14 decomposition of trichloroethylene (Cl₂C=CHCl, TCE), bromomethane (CH₃Br),
15 and tetrafluoromethane (CF₄). They showed that residence time was the most
16 important parameter in the decomposition rates of CH₃Br and CF₄ and therefore,
17 FPR and SDR have shown higher performance than PCR. Yamamoto et al. [32]
18 employed a hybrid plasma reactor followed by a chemical reactor to optimise the
19 performance of the reactor for NO_x removal. They showed that by decreasing the
20 gas flow rate and therefore increasing the residence time, more NO_x can be removed

1 from the exhaust gas. Urashima and Chang in 2000 [33] showed the same results for
2 volatile organic compounds.

3 Residence time is recognized as an important parameter for plasma reactor
4 performance. Therefore, it is important to optimize the residence time in the design
5 of NTP reactor. The objective of the present study is to increase the residence time
6 of the NTP reactor and then study its effect on NO_x removal efficiency. For this
7 purpose, different kind of screw thread electrodes with non-helical structure and
8 different gap-length between the threads, as well as a rod electrode are studied. For
9 different electrode configurations, NO_x removal is investigated experimentally and
10 the residence time is calculated numerically. Note that the residence time distribution
11 (RTD) is obtained using the commercial Fluent software.

12 **Experimental setup**

13

14 The experimental setup consists of the plasma reactor, high voltage pulse power
15 supply, the gas feeding and the measurement systems [34]. The plasma reactor is a
16 DBD reactor which is shown in Fig. 1. The geometry of the reactor is similar to the
17 curved plasma actuators [35-37]. It is a coaxial type reactor made up of an outer
18 quartz glass tube (>99.9% SiO₂) with a total length of 400 mm and inner diameter
19 of 12 mm. For the inner corona electrode, an aluminum rod (with and without thread)
20 is used along the axis of the cylinder and an aluminium mesh is wrapped over the

1 quartz glass tube of the outer electrode, which acts as a grounded electrode.
2 Aluminium material was chosen due to its cheap cost and large secondary electron
3 coefficient by nitrogen ion bombardment [38]. Fig. 1 shows a cross-sectional view
4 of the reactor to enable a cleaner view of the various parts of the reactor.

5 Two different electrode configurations (rod and screw thread electrodes) are
6 examined. The rod corona electrode consists of an aluminium rod with a diameter
7 of 10 mm. The screw thread configurations of the corona electrodes consist of
8 threaded rods with 1 mm thread height and 1, 2 and 3 mm gaps between the threads.
9 The plasma is generated using a high-voltage DC-pulse waveform pulsed power
10 system. The range of output voltage of the DC power supply was 0-5 kV at
11 maximum current of 1A. The voltage is raised by a pulse transformer (winding ratio
12 of 5:30). The DC-pulse voltage repetition rate of 10-30 kHz and peak to peak
13 discharge voltage of 0-20 kV across the DBD load is generated and applied to the
14 reactor. The gas system used in this study consists of two pure NO_x and N₂ cylinders.
15 By balancing the ratio of each gas by adjusting the valves and regulators, the mixture
16 is provided in order to have a total flow rate of 8 L/min and an initial NO_x
17 concentration of almost 720 ppm. Note that the concentration of NO_x is measured
18 by means of a chemiluminescence gas analyzer (AVL DI GAS 4000).

19 **CFD Modelling**

20

1 For evaluating the gas residence time, the Navier-Stokes equation that governs the
2 fluid flow is first solved. Then, by using the resulting flow velocity field, the
3 concentration equation is then solved to find the residence time distribution for a
4 given configuration.

5 **Fluid flow modelling**

6
7 For the given gas flow rate and reactor geometry, a steady state, laminar,
8 axisymmetric model is used to find the velocity field. An axisymmetric model is
9 appropriate for this case since there are zero or negligible circumferential gradients
10 in the flow; however, there may be non-zero circumferential velocities.

11 **Residence time distribution modelling**

12
13 The residence time distribution (RTD) is determined by injecting an inert tracer into
14 the reactor at time $t = 0$ and then measuring the tracer concentration, C , in the
15 effluent stream as a function of time. There are two methods of injecting tracer into
16 a reactor: pulse input and step input. In a pulse input, a specific amount of tracer, N_0
17, is suddenly injected in one shot into the feed stream, entering the reactor as quickly
18 as possible. The outlet concentration is then measured as a function of time ($C(t)$).
19 The amount of tracer material, ΔN , leaving the reactor between time t and $t + \Delta t$
20 is then,

$$\Delta N = C(t)V\Delta t \quad (1)$$

1 where V is the volumetric flow rate. Then, by dividing N_0 on both sides, it follows
2 that,

$$\frac{\Delta N}{N_0} = \frac{C(t)V}{N_0} \Delta t \quad (2)$$

3 which represents the fraction of material that has a residence time in the reactor
4 between time t and $t + \Delta t$. The residence-time distribution function is then defines
5 as,

$$E(t) = \frac{C(t)V}{N_0} \quad (3)$$

6 This function describes quantitatively how much time various fluid elements
7 spent in the reactor. When N_0 is not known directly, it is evaluated from the outlet
8 concentration measurements by summing up all ΔN 's over time (from zero to
9 infinity). Writing Eq. (1) in differential form gives:

$$dN = C(t)Vdt \quad (4)$$

10 and then by integrating gives:

$$N_0 = \int_0^{\infty} C(t)Vdt \quad (5)$$

11 The volumetric flow rate V is usually constant, hence $E(t)$ can be defined
12 as:

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t) dt} \quad (6)$$

1 As is the case with other variables described by distribution functions, the
 2 mean value of the variable is equal to the first moment of the RTD function, $E(t)$.
 3 Thus the mean residence time is:

$$\tau = \frac{\int_0^{\infty} tE(t) dt}{\int_0^{\infty} E(t) dt} = \int_0^{\infty} tE(t) dt \quad (7)$$

4 In this paper, Fluent software is also employed to solve the concentration
 5 equation with the convection and diffusion terms to model the tracer transport and
 6 evaluate the residence time [39]. The concentration equation is as,

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = D \nabla^2 c \quad (8)$$

7 where c denotes the concentration (kg/m^3), D is diffusion coefficient (m^2/s),
 8 and \mathbf{u} refers to the velocity vector (m/s). The velocity vector field is given by
 9 solution of the Navier-Stokes equations under steady state condition.

10 **Results and discussion**

11 **Grid dependency study**

12

1 To make sure that the resulting solution is grid independent, CFD simulations of the
 2 velocity distribution and the mean residence time are evaluated for different
 3 computational grid sizes for the screw electrode with 1 mm gap between the threads.
 4 Three different grids are considered. The characteristics of the grids are listed in
 5 Table 1. All the grids are uniform quadrilateral mesh with different numbers of nodes
 6 in the x and r direction. More details of the computational domain are described in
 7 the next section. Figs. 2-a and 2-b show the velocity profiles, respectively, at
 8 $x = 10\text{ cm}$ and $x = 30\text{ cm}$. It is seen that there is almost no variation for different
 9 meshes. However, a close inspection of Fig. 2-b shows that the mesh with 45,000
 10 grids results in a small deviation in the velocity profile at low values of r .

11 The results of the achieved residence time are shown in Table 1. This table
 12 shows that there is no significant difference between the calculated residence times
 13 when the grid with 130,000 and 360,000 cells are used.

14

Table 1. Grid dependency analysis of RTD.

Number of cells	Number of cells in r direction for 1 mm	Number of cells in x direction for 1 mm	Residence time at $x = 10\text{ cm}$	Residence time at $x = 30\text{ cm}$	Plasma reactor residence time
45,000	20	5	0.026057	0.0888028	0.062746
130,000	30	10	0.026052	0.0888760	0.062824
360,000	40	20	0.026051	0.0888810	0.062830

15

1 Based on the results presented in Fig. 2 and Table 1, the grid with 130,000
2 cells is selected for the rest of the computational analysis. For the selected mesh, the
3 convergence criterion for the continuity and velocity decreases to about $1e^{-13}$ after
4 1,500 iterations and then remains constant with increasing number of iterations. Note
5 that to increase the accuracy of the results, the double precision condition is used for
6 these computations.

7 **Study the effect of electrode configuration on the residence time:** 8 **numerical study**

9
10 One of the conventional methods for improving RTD is adding the baffles inside the
11 reactor. Three different screw thread configurations of electrode as well as a rod
12 electrode are examined in this study. Screw thread electrodes actually behave as
13 baffles inside the reactor. The height of the threads is fixed at 1 mm and the gaps
14 between threads and also the thread width are changed in these simulations. Three
15 different gaps including 1, 2 and 3 mm are studied. Note that the length of the threads
16 is equal to the gap between the threads in all cases. Fig. 3 shows an image of the
17 studied screw thread electrodes with non-helical structures.

18 Fig. 4 displays a schematic view of the computational domain for the reactor
19 inside and description of different parameters. As shown in this figure, “a” and “b”
20 are, respectively, the height and the width of the thread, and “t” is the distance
21 between two threads. As mentioned before, “a” is fixed at 1 mm, and “b” and “t”

1 are the same, and are equal to 1, 2 and 3 mm for the three studied electrodes. Note
2 that the plasma is generated from the beginning of the threads to the end of the
3 threads. The total length of the electrode and threads are, respectively, 40 and 20 cm.
4 Therefore, RTD is evaluated at 10 cm and 30 cm from the inlet, and the difference
5 between the residence times at these two points is considered as the residence time
6 of the flow inside the plasma reactor.

7 In all models, a gas flow rate of 8 L/min, which corresponds to the inlet
8 velocity of approximately 3.86 m/s is assumed. Based on this velocity, the Reynolds
9 number is very low and therefore, the flow is in laminar regime. A constant velocity
10 at the inlet and an outflow condition at the outlet are used for the boundary
11 conditions. No slip boundary condition is imposed on all solid surfaces.

12 Fig. 5 displays the RTD for the screw thread electrode with 1 mm gap between
13 the threads at $x = 10\text{ cm}$ and $x = 30\text{ cm}$ inside the reactor. As mentioned before,
14 the first moment of RTD, $E(t)$, is calculated at the points of $x = 10\text{ cm}$ and
15 $x = 30\text{ cm}$ and then by subtracting these two mean values, the residence time for the
16 exhaust flow in the plasma reactor is determined. Table 2 lists the calculated
17 residence time for all the studied reactors. The residence time for all models with
18 the screw thread electrodes is higher than those for the rod electrode without any
19 thread. Furthermore, the reactor with 1 mm distance between the threads has the

1 highest residence time. The increase in the RTD significantly affect the plasma
 2 emission reduction [40].

3

Table 2. Calculated residence time for various studied electrodes

Electrode type	Residence time at x = 10 cm	Residence time at x = 30 cm	Plasma reactor residence time
Screw thread electrode (b = 1 mm)	0.02605	0.08909	0.06303
Screw thread electrode (b = 2 mm)	0.02605	0.08899	0.06294
Screw thread electrode (b = 3 mm)	0.02605	0.08888	0.06282
Rod electrode	0.02605	0.07790	0.05185

4

5 The reason for the increase in residence time in the reactors with screw thread
 6 electrodes is an increase in the mean cross sectional area of fluid flow, and also the
 7 formation of vortices inside the thread and as a result, the increase in the circulation
 8 of flow inside the thread. Therefore, by increasing the residence time, the gas
 9 exposure to plasma increases, and the probability of the electron impact reactions
 10 and also secondary reactions for emission reduction increases [1]. Thus, higher NO_x
 11 removal can be achieved with the screw thread electrode [28]. Furthermore, the
 12 existence of the threads increases the surface area and contact between the
 13 electrode's wall and the fluid, which is the most important area in the reactor for
 14 NO_x removal. Therefore, increasing the area of the inside electrode increases NO_x

1 removal from the exhaust due to the occurrence of higher discharge power near the
2 wall.

3 Fig. 6 displays the velocity vector fields for different reactors. The formation
4 of recirculating vortices inside the threads is clearly seen from this figure. For the
5 screw electrode with 1 mm thread length, the residence time is higher than those for
6 the other electrodes. This is because, the number of 1 mm threads in the screw
7 electrode is higher than those with larger size threads.

8 Fig. 7 shows the velocity magnitude at the middle of the thread for the screw
9 thread electrode with 1 mm thread width. This figure shows that inside the thread, a
10 reverse flow due to the formation of a recirculation flow is formed; therefore, higher
11 residence times are achieved.

12 **Study the effect of electrode configuration on NO_x removal:** 13 **experimental study**

14
15 In an NTP reactor, NO_x concentration is reduced by a set of reactions between free
16 electrons, ions, radicals, atoms and molecules which are formed in plasma [1, 41-
17 46]. Furthermore, due to the high rate of ozone production in the plasma actuators
18 in atmospheric condition, ozone has an important effect on NO_x reduction [1, 47-
19 49].

1 In this study, the performance of non-thermal plasma is evaluated by considering
 2 different parameters including NO_x removal efficiency, specific energy density and
 3 NO_x energy efficiency.

4 To parametrize the amount of reduced NO_x from the exhaust gas, the NO_x removal
 5 efficiency is defined as:

$$NOx_R = \frac{NOx_i - NOx_f}{NOx_i} \times 100 \quad (9)$$

6 where NOx_i (in ppm) and NOx_f (in ppm) are , respectively, the initial (before
 7 treatment) and the final (after treatment) concentrations of NOx in the gas mixture.

8 Specific energy density (SED) is defined as the ratio of discharge power to
 9 the gas flow rate. That is [50]:

$$SED = \frac{P \times 60}{G} \quad (J/l) \quad (10)$$

10 where P and G are the discharge power (W) and the flow rate (L/min),
 11 respectively.

12 Another important parameter is the relationship between the consumed power
 13 and the reduced NO_x concentration. Accordingly, the NO_x energy efficiency (NOx_E
 14) is defined as [15]:

$$NOx_E = \frac{G}{22.4} \times (NOx_i - NOx_f) \times 60 \times 10^{-3} \times 76}{E} \quad (g/kWh) \quad (11)$$

1 where E (W) is the input power to the reactor. In the above equation, 76 is the
2 molecular weight of 1 mol NO_x ($NO+NO_2$).

3 Figs. 8-a and 8-b, respectively show the effect of different electrode
4 configurations on NO_x removal efficiency at 9.9 kV_{PP} , and different pulse
5 frequencies and at the frequency of 19.2 kHz and various applied voltages. Note that
6 V_{PP} is the peak-to-peak discharge voltage applied to the reactor. This figure shows
7 that the screw thread electrodes have higher removal efficiency than the rod
8 electrode at all applied voltages and frequencies. Furthermore, among all the screw
9 thread electrodes, the electrode with a thread width of 1 mm has the best
10 performance. It should be noted that the experiments are conducted at three different
11 applied voltages of 7.1, 8.7 and 9.9 kV_{PP} and six different frequencies of 13.4, 16.6,
12 19.2, 21.9, 24.5 and 27.2 kHz. All the obtained NO_x removal efficiencies for all
13 applied voltages and frequencies as well as all selected electrode types are available
14 in the supporting information (S1 Table).

15 As expected, NO_x removal efficiency is increased by increasing the applied
16 voltage due to the increase in the electric field intensity and as a result by production
17 of high-energy electrons [46, 51]. Moreover, increasing the pulse frequency results
18 in a higher input energy due to the higher rate of charge and discharge of the storage
19 capacitor in the pulse power system. Consequently, the rate of electrons, ions and

1 radicals production and the effective collisions of them increases, which causes an
2 increase in NO_x reduction [52, 53].

3 The reason for the better preference of the screw thread electrodes over the
4 rod electrode can be explained according to the residence time and discharge power.
5 Note that in [34], it was shown that by using a 1 mm screw thread electrode in the
6 DBD reactor, the discharge power increases and therefore, the produced plasma is
7 more intensive and higher removal of NO_x can be achieved. Therefore, this study is
8 focused on the effect of residence time. By increasing the residence time of the gas
9 inside a plasma reactor, generally, the gas exposure to the electric field in the reactor
10 increases, and more NO_x removal can be achieved.

11 Fig. 9 shows the dependence of NO_x removal efficiency as a function of SED
12 for different screw thread configurations and for the rod electrode.

13 It is seen that the screw-shaped electrode with 1 mm gap between the threads
14 has the best performance for NO_x removal efficiency. The reason is that by
15 increasing the thread number in the length of the corona electrode, as discussed as
16 the numerical section, a higher residence time and a higher discharge power [34] is
17 achieved and therefore, the ability of NTP for removing NO_x from the simulated gas
18 increases.

19 Fig. 10 displays the variation of NO_x removal efficiency as a function of NO_{xE}
20 for different studied models. This figure shows that the efficiency of NO_x removal

1 is higher at the lower NO_{xE} and is decreased by increasing the energy efficiency of
2 NO_x . Furthermore, at high NO_x removal efficiency, the reactor with 1 mm screw
3 thread width electrode has the lower NO_{xE} than the other reactors. However, the
4 reactor with 2 mm screw thread width electrode with a thread width of 2 mm has the
5 best performance in the other range of NO_x removal efficiency.

6 It should be noted that the residence time is believed to be a critical parameter
7 for plasma NO_x removal. Therefore, the present CFD simulation study was
8 performed to find the optimized configuration in terms of the residence time. As it
9 was shown in Figs. 8-10, the positive effects of increasing the residence time was
10 confirmed by the increase in NO_x removal in the experiment.

11 Another reason that shows the screw thread electrode to be preferred over the
12 rod electrode is the formation of micro-discharges. In the screw thread electrode,
13 due to the presence of sharp corners, micro-discharges are formed more than that for
14 the rod electrode. In other words, the screw thread electrode consists of a number of
15 edges of threads for the summing of electrical charges. In plasma chemistry, the
16 plasma chemical reactions' efficiency in the discharge gap depends on the amount
17 of transported charges in micro-discharge channels [34, 54]. Therefore, the screw
18 electrode generates a large number of micro-discharges with a small energy
19 deposition per micro-discharge [55].

1 Fig. 11 displays an image of the produced discharge and micro-discharge in
2 the plasma for the screw thread electrode with 1 mm thread width. The produced
3 micro-discharges can be seen in this figure. Note that the number of sharp corners is
4 higher in the screw thread electrode with 1 mm thread width than those for 2 mm
5 and 3 mm treads; therefore, this provides another reason for screw thread electrode
6 with the thread width of 1 mm to be preferred over the other studied electrodes.

7 **Conclusions**

8
9 In this paper, a computation model for evaluating the residence time distribution of
10 a conventional DBD reactor was presented. Different electrode configurations were
11 studied in order to increase the reactor residence time and the subsequent NO_x
12 removal efficiency. It was shown that adding an appropriate thread configuration to
13 the electrode can increase the residence time of the exhaust passing through the
14 reactor, due to the formation of recirculating flows inside the threads. Furthermore,
15 adding thread to the electrode increased the sharp corners in the reactor, which
16 produced a higher streamer and as a result a higher discharge current. The results
17 showed that the screw thread electrode with a thread width of 1 mm had the best
18 performance among the electrodes studied with respect to the residence time and
19 NO_x removal efficiency. The residence time of the screw thread electrode with 1mm
20 thread width is almost 21.6% higher than that for the rod electrode which led to about

1 7.5% more NO_x removal efficiency compared to the rod electrode at the highest
2 studied voltage and frequency. It should be emphasized that the present study was
3 focused on the residence time of the gas inside the reactor in the absence of plasma
4 and electric field. Therefore, this provides an initial step as the base line for the more
5 extensive future studies that includes these other important effects.

6

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3 **Figure captions**

4

5 **Fig. 1. A coaxial DBD reactor.** Purple color represents the generated non-thermal
6 plasma in the DBD reactor.

7 **Fig. 2. Grid dependency analysis of velocity magnitude.** a) $x = 10$ cm b) $x = 30$
8 cm

9 **Fig. 3. Image of the screw thread electrodes.**

10 **Fig. 4. Schematic of the computational domain for studying the effect of threads**
11 **on RTD.**

12 **Fig. 5. RTD at $x = 10$ cm and $x = 30$ cm inside the reactor for the screw thread**
13 **electrode with 1 mm gap between the threads.**

14 **Fig. 6. The velocity vector field of flow inside the reactors with different threads.**

15 a) Screw thread electrode with 1 mm thread length, b) Screw thread electrode with
16 2 mm thread length, c) Screw thread electrode with 3 mm thread length, d) The rod
17 electrode without any threads.

18 **Fig. 7. Velocity vectors of the flow at the middle of the thread for the reactor**
19 **with the screw thread electrode with 1 mm gap between the threads.**

1 **Fig. 8. Effect of electrode configuration on NO_x removal efficiency. a)** at 9.9 kV_{PP}
2 and different pulse frequencies b) at 19.2 kHz pulse frequency and different applied
3 voltage.

4 **Fig. 9. The variation of NO_x removal efficiency as a function of SED for various**
5 **studied electrodes at 9.9 kV_{PP}.**

6 **Fig. 10. The variation of NO_x removal efficiency as a function of NO_{xE} for**
7 **different electrode configurations.**

8 **Fig. 11. An image of the produced plasma for the reactor with screw electrode**
9 **with 1 mm gap between the threads.**

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12 **Supporting Information**

13

14 **S1 Table. NO_x removal efficiency for different studied electrode types at**
15 **different applied voltages and pulse frequencies.**

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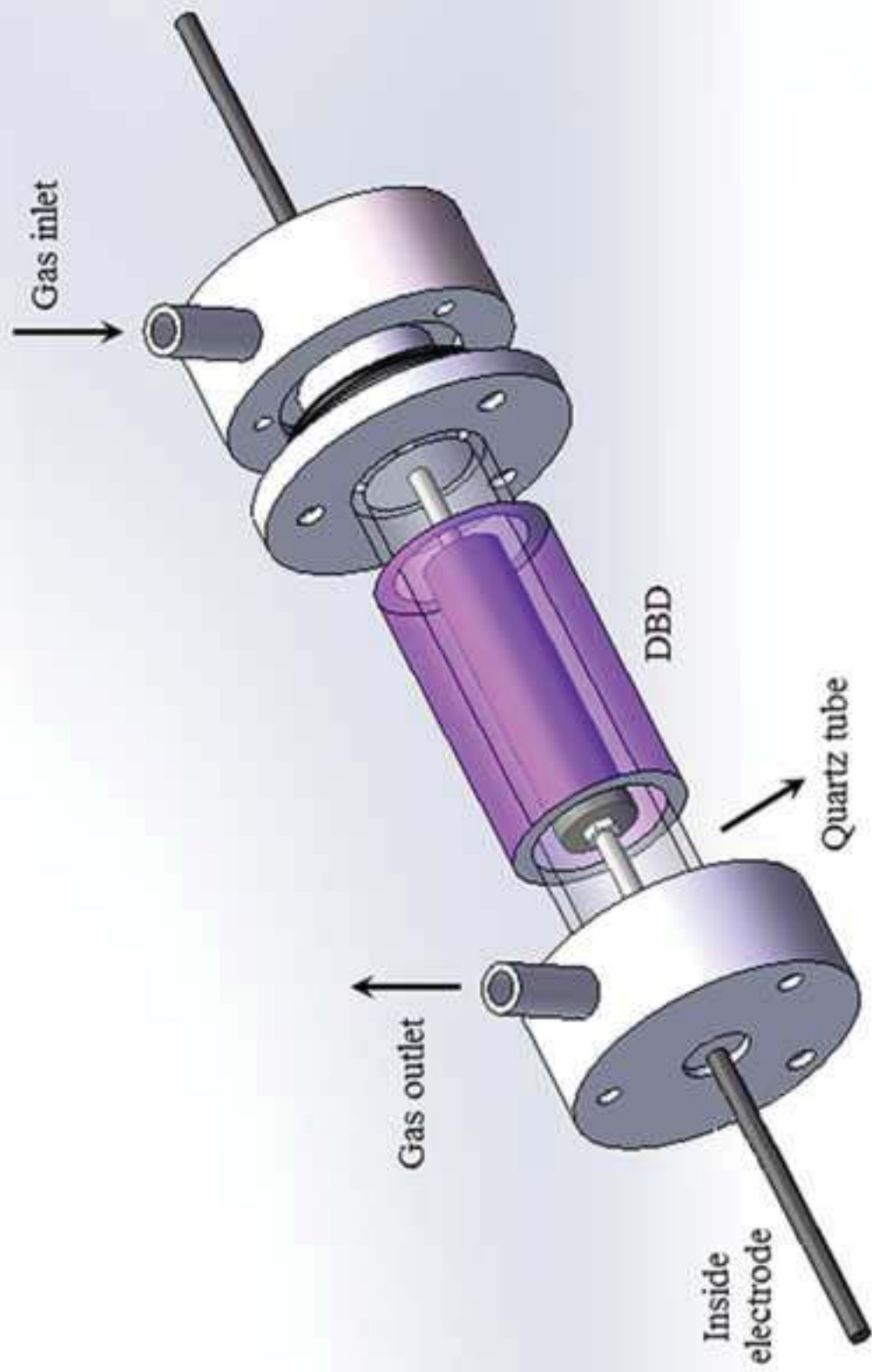


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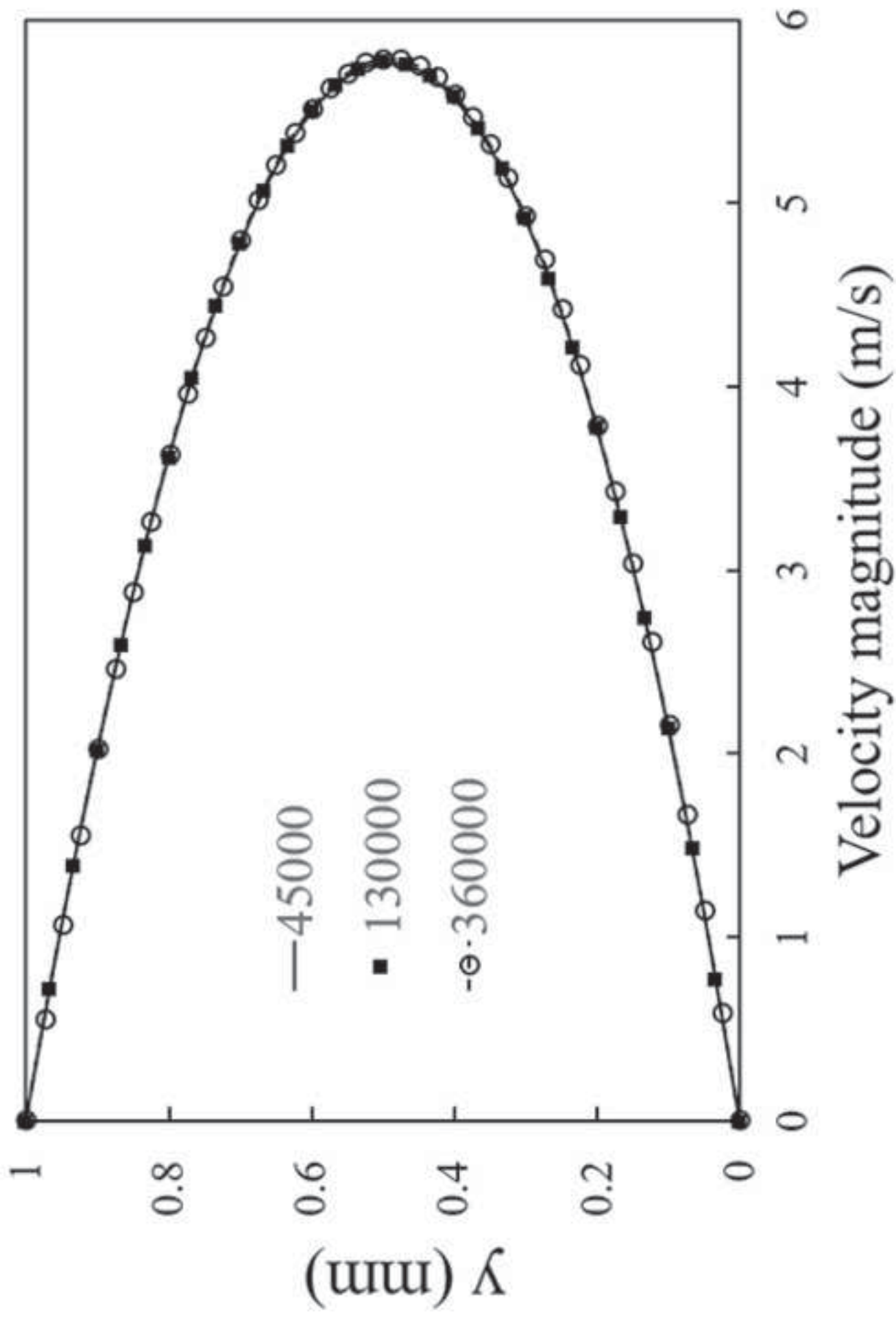


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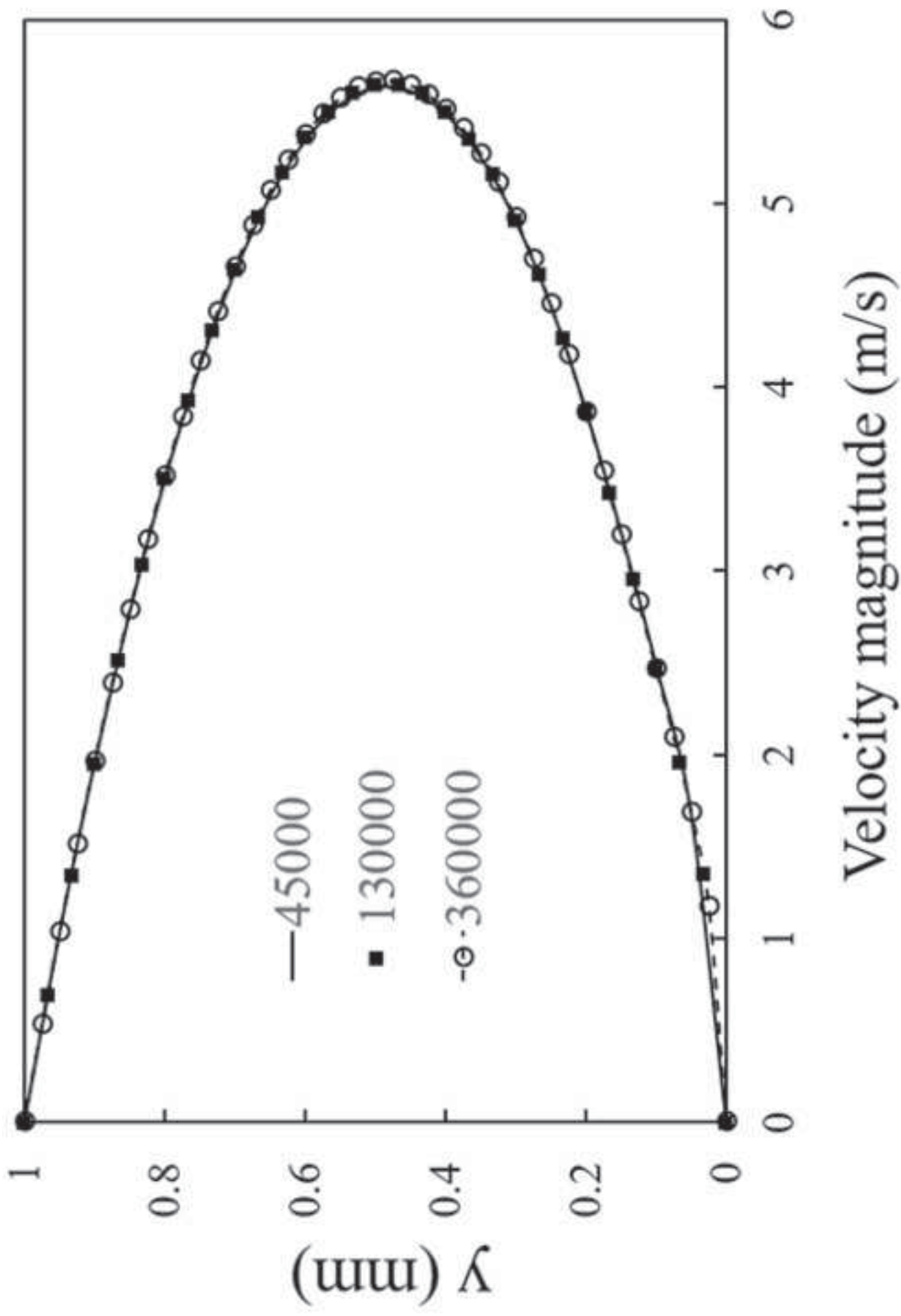


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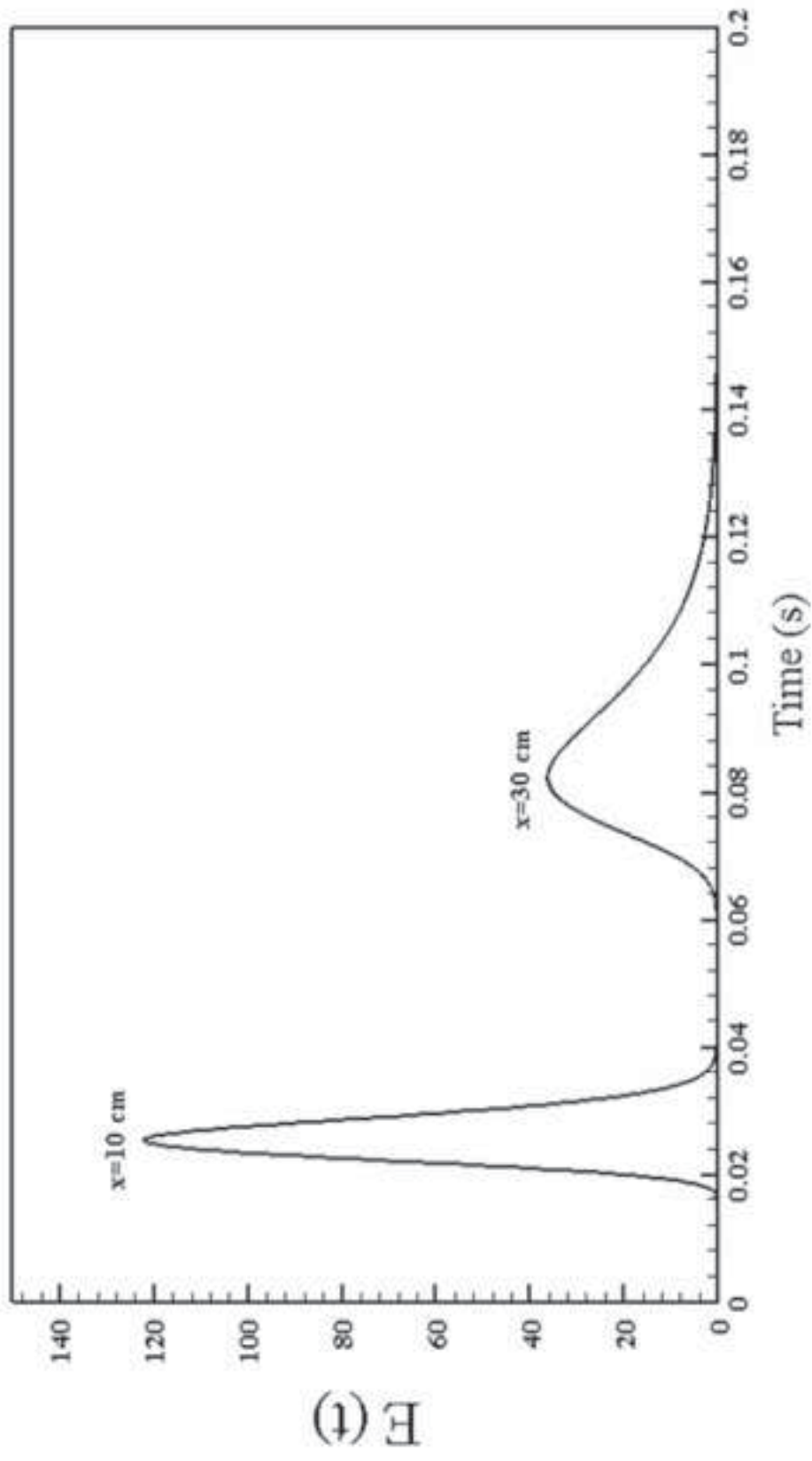


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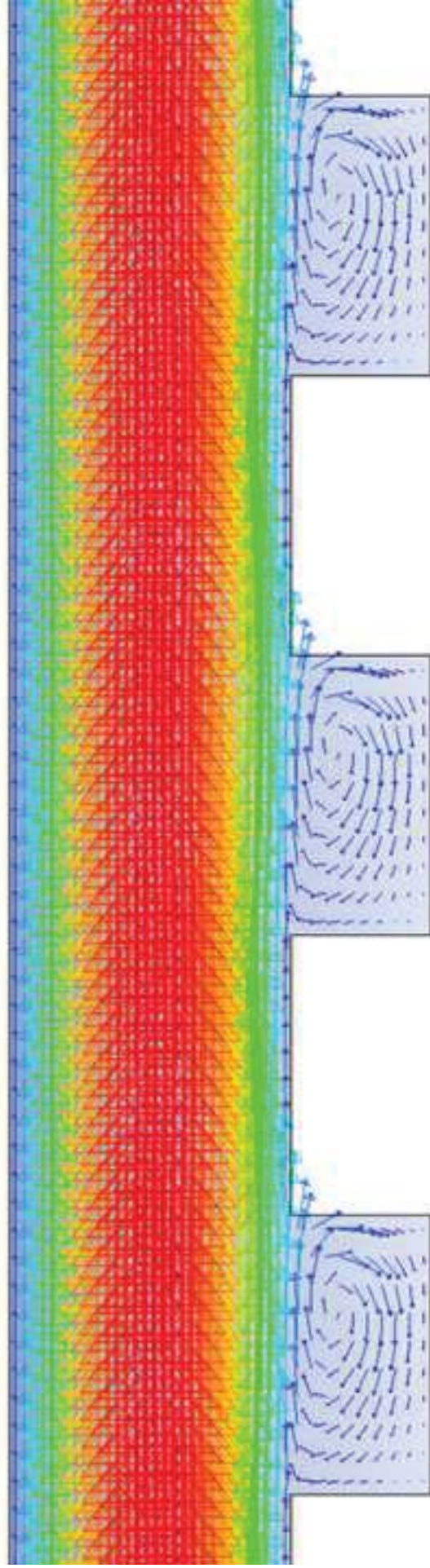


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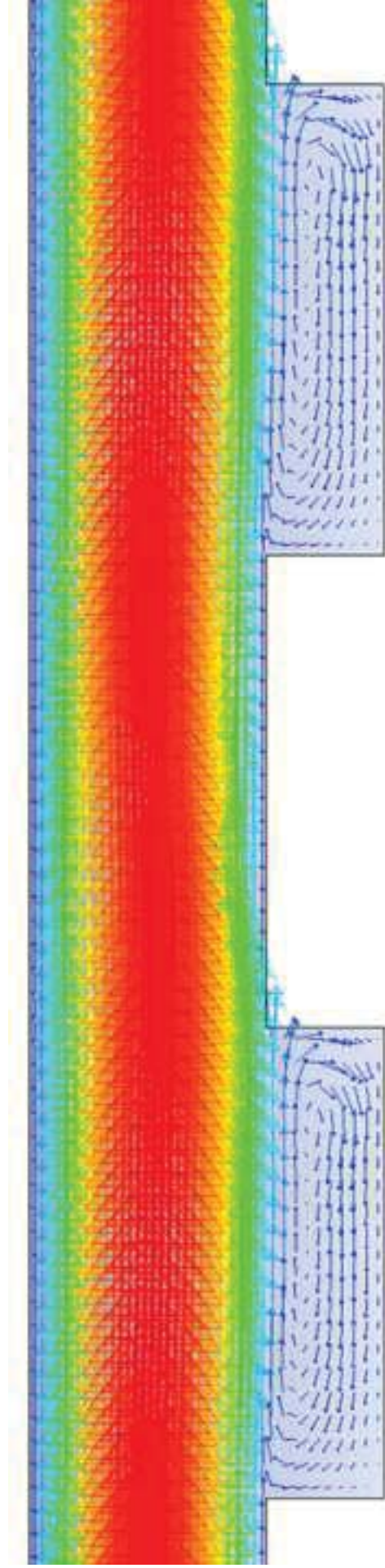


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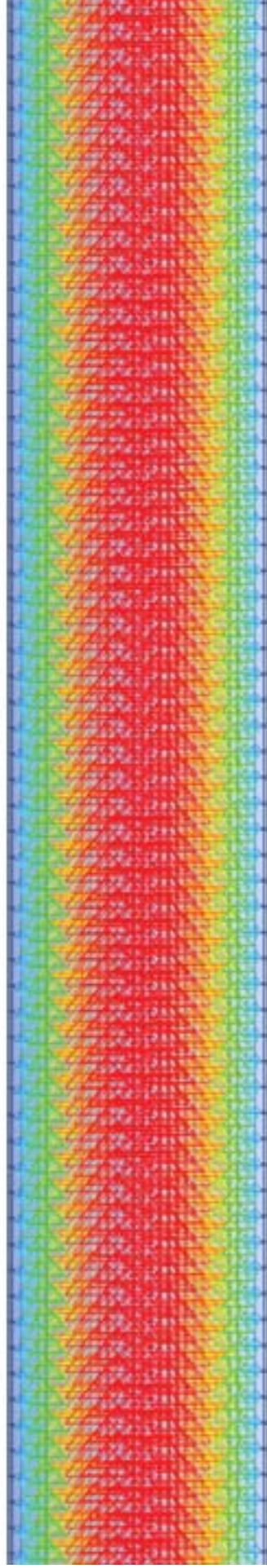


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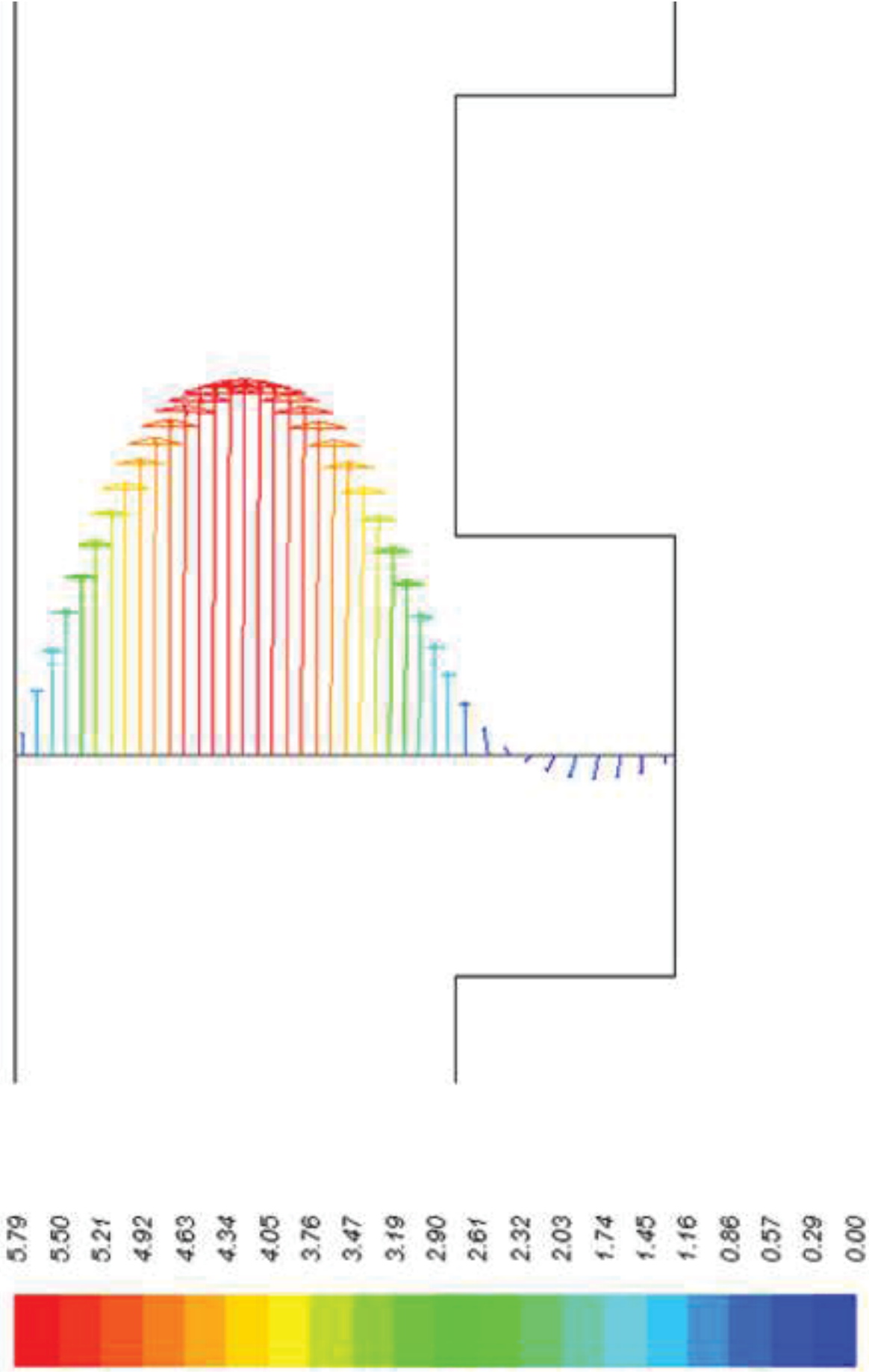


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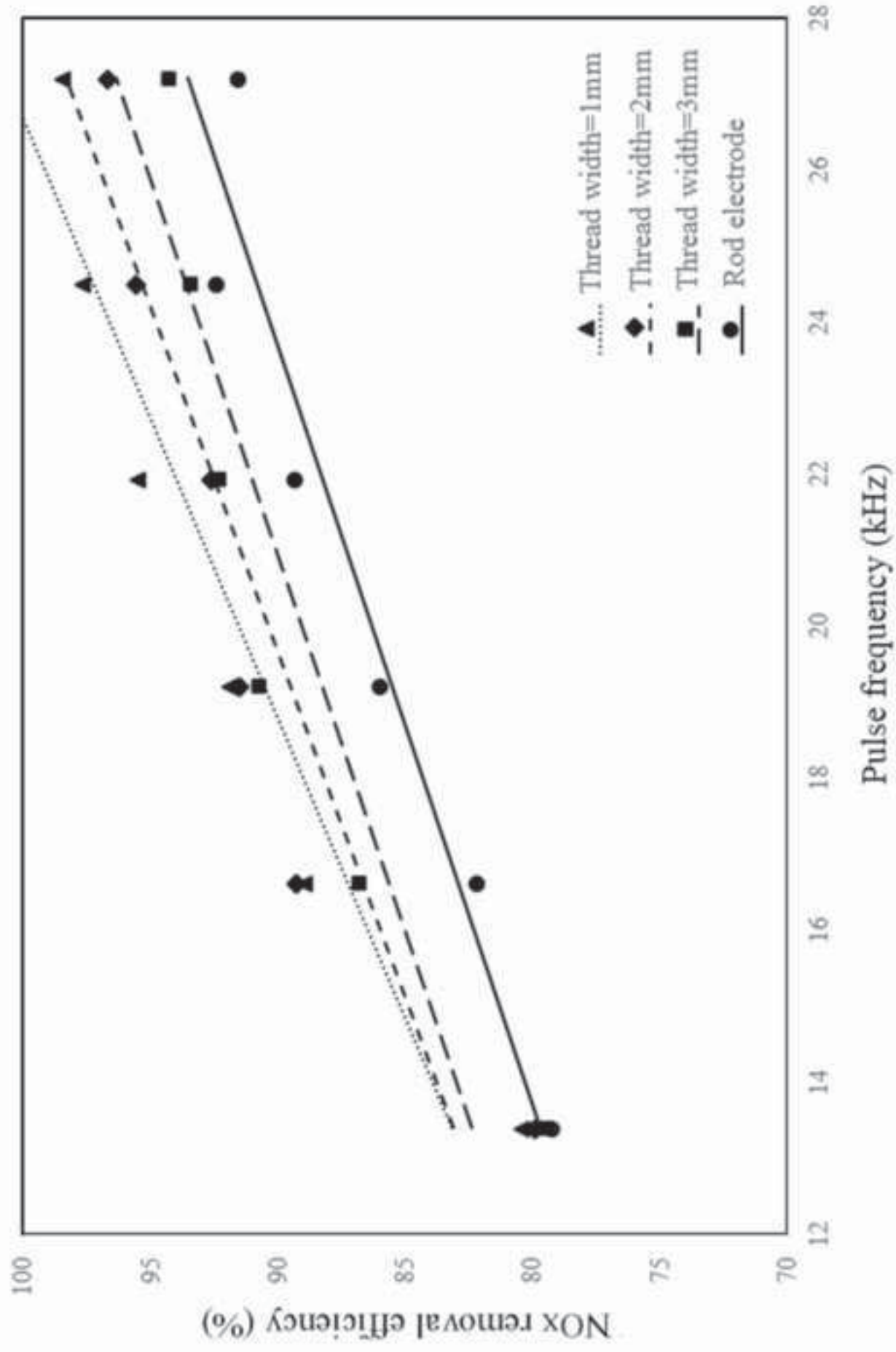


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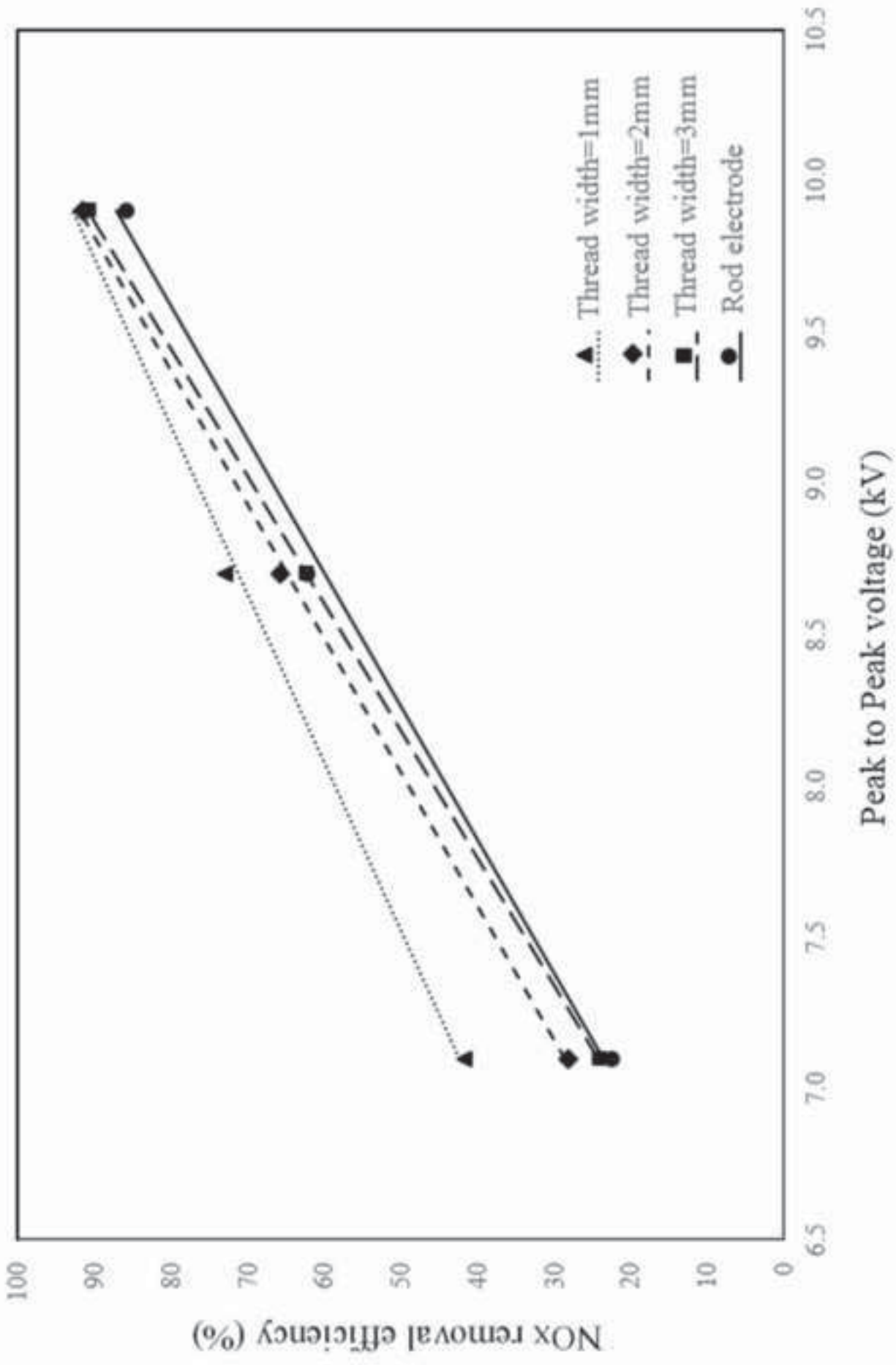


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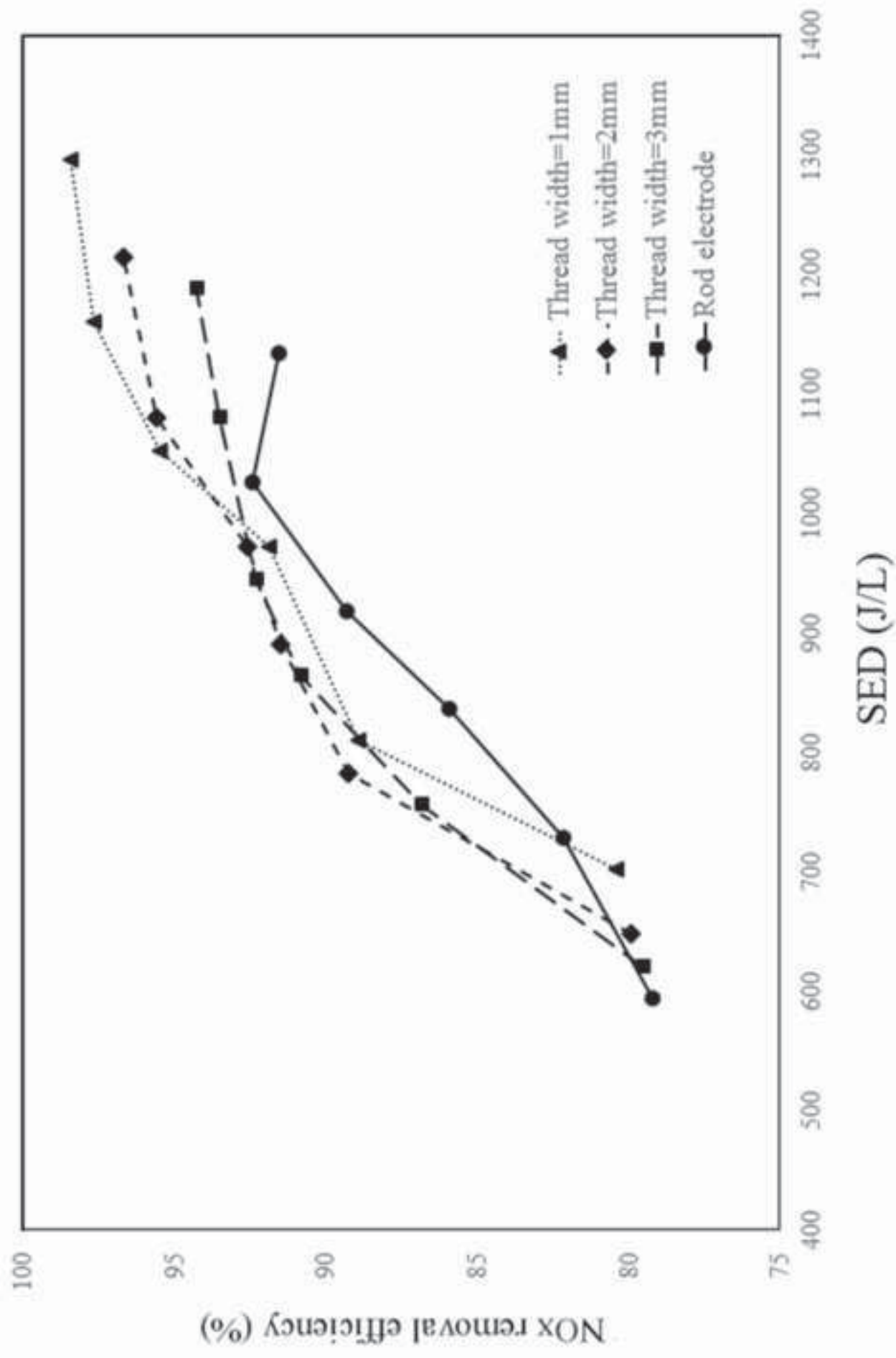
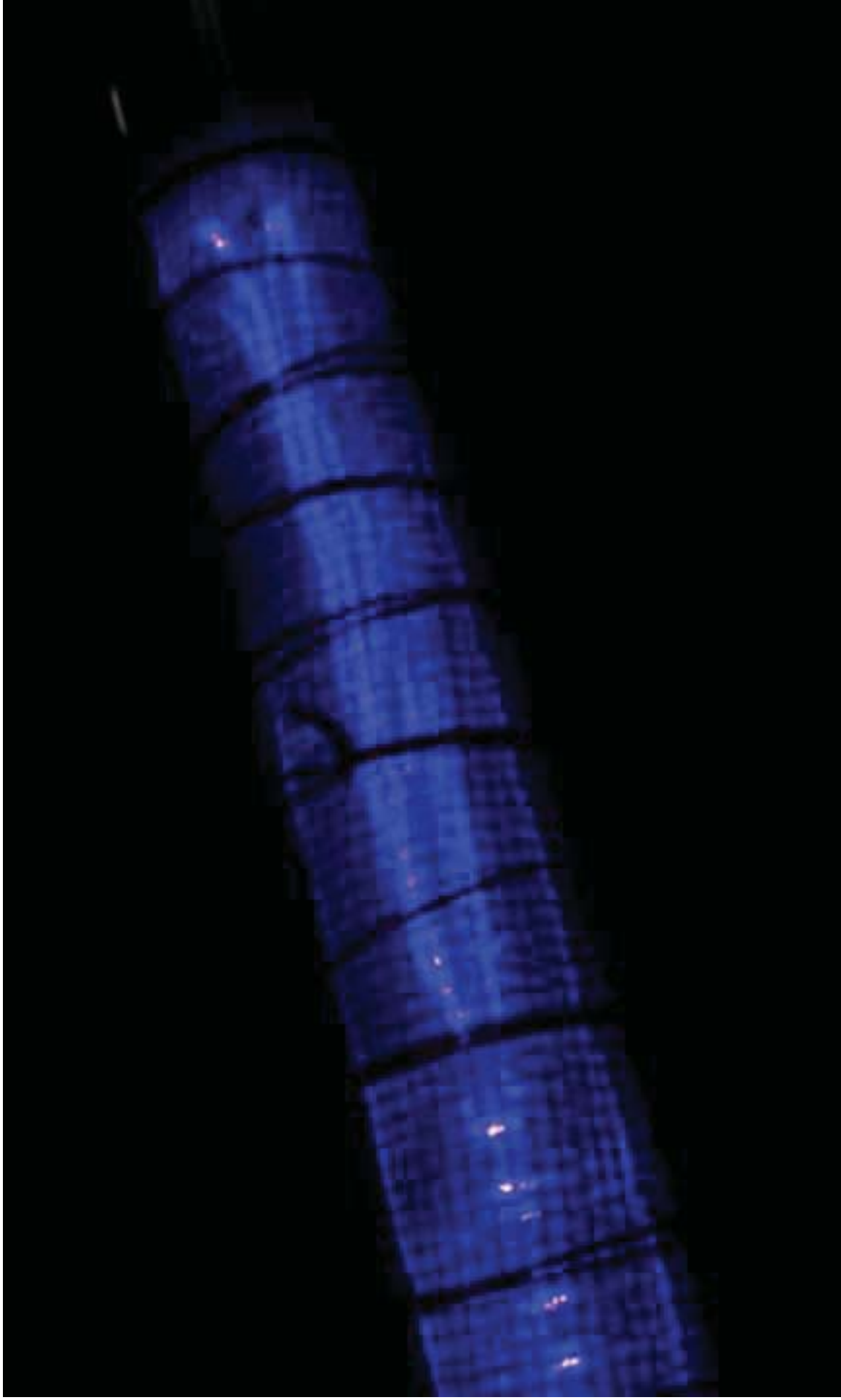


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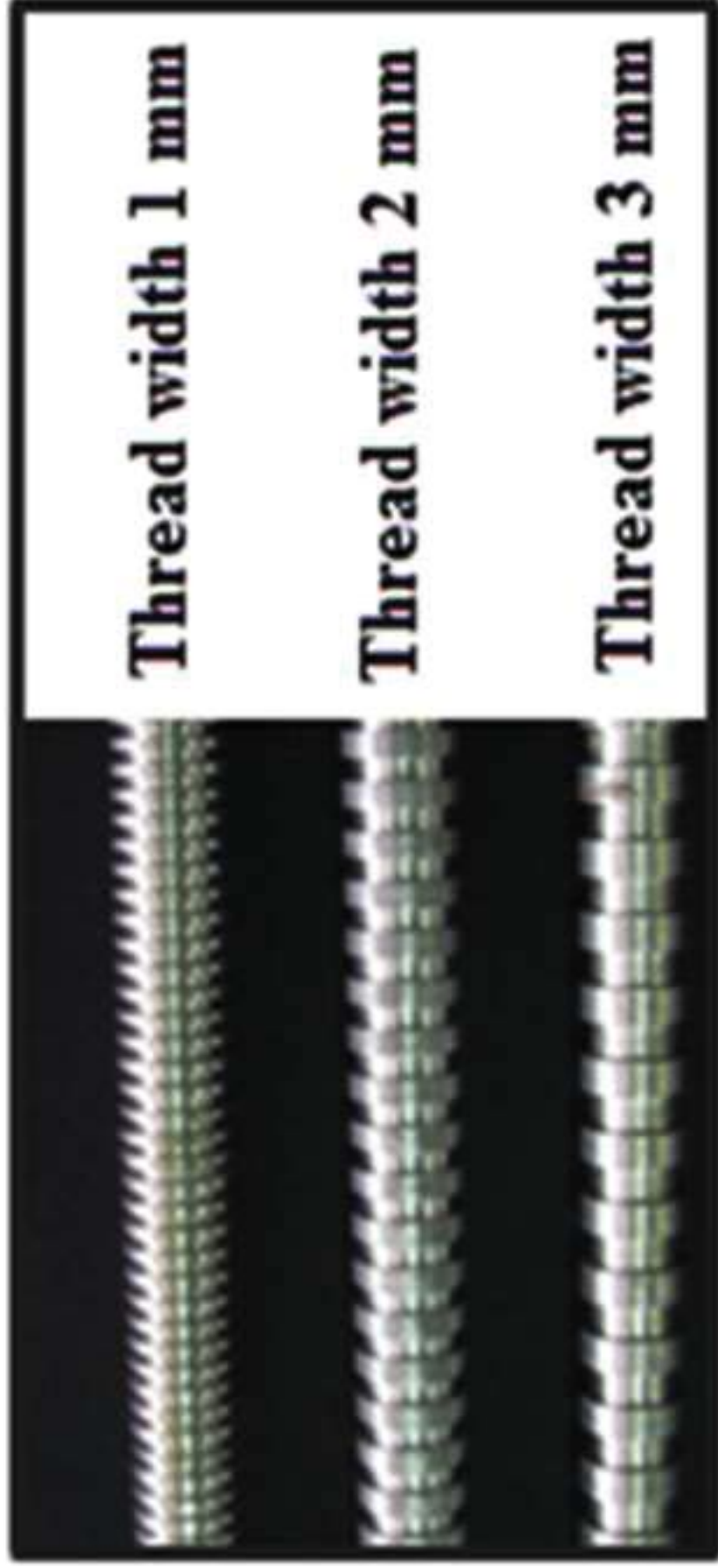


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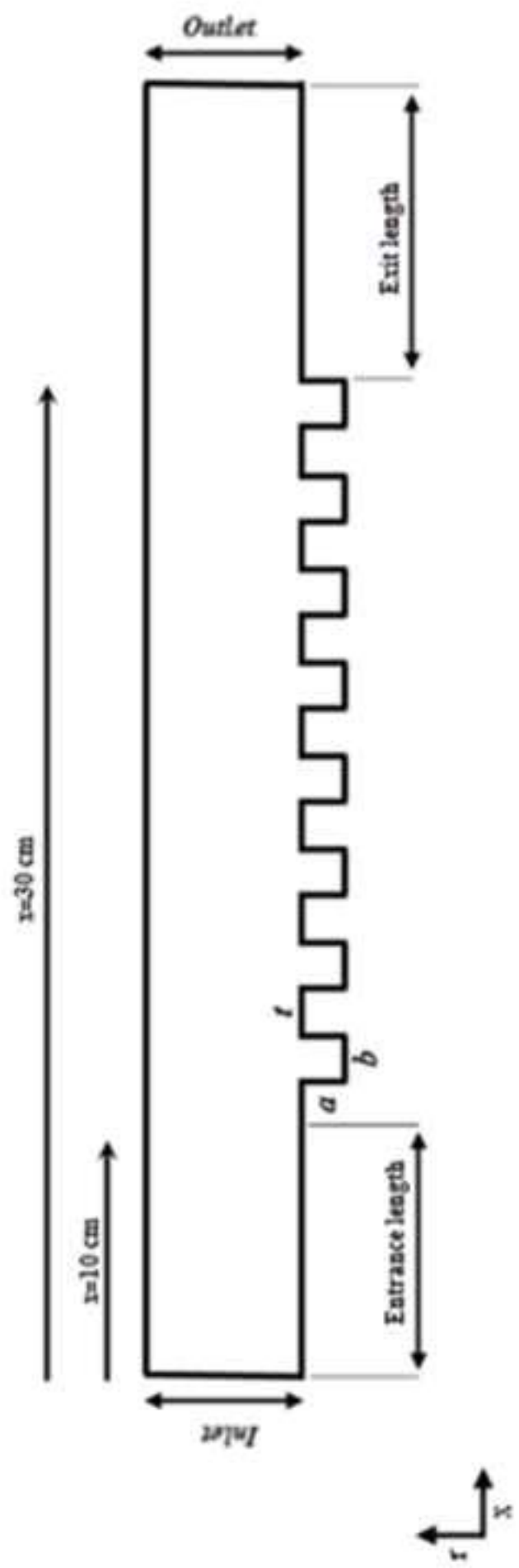


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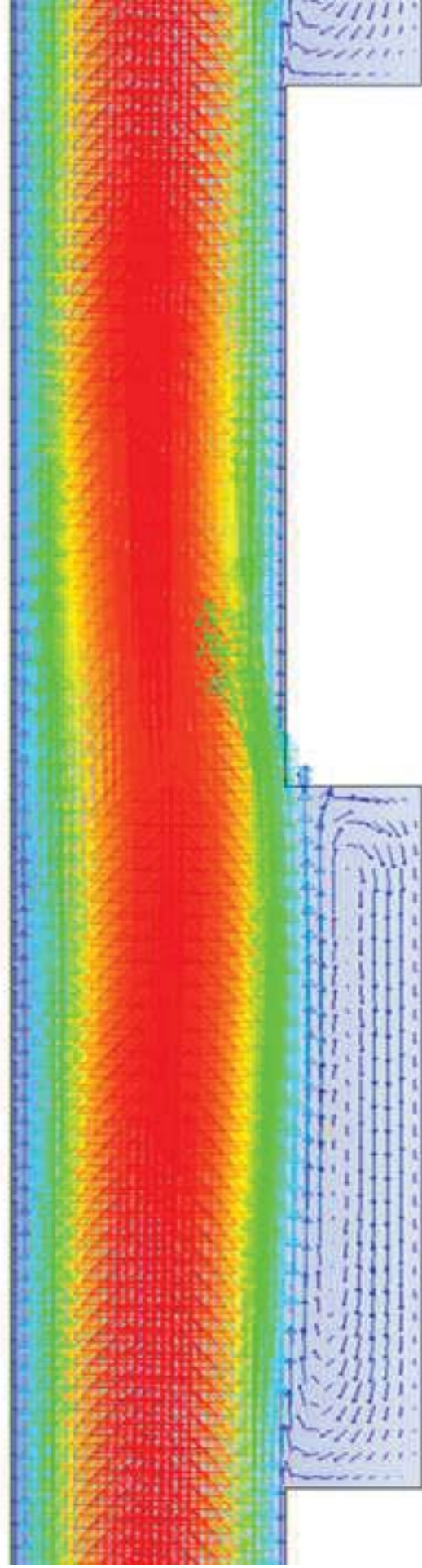


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