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2025

International Journal of Thermal Sciences 208 (2025) 109513

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Analytical model for laser cutting in porous media

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ARTICLE INFO

Keywords:
Laser cutting
Useful and waste power
Analytical model
Porous media
Heat transfer

ABSTRACT

Laser cutting in porous media presents both challenges and opportunities for various applications. Laser cutting requires a deep understanding of heat transfer, materials, and laser physics, and can involve nonlinear and transient effects. There is a lack of literature regarding modelling laser cutting in porous media. Using conservation of energy principle, an analytical model has been developed to calculate the total laser power required to cut a porous media without the need for complex numerical simulations.

The model incorporates a new correlation for calculating waste power due to heat transfer into the surrounding during laser cutting as well as modifications to the energy balance equation to incorporate the effect of porosity and fluid saturation.

The model has been validated with experimental data of cutting porous media (carbonate rock) and corroborated well. Model validation showed around 10 % accuracy for fluid saturated rock samples and around 17 % accuracy for dry rock samples. Also it has been observed that the level of accuracy improves with lower Peclet number (i.e. lower cutting speed).

The proposed analytical model has been used to examine the effect of Peclet number, porosity, fluid saturation, rock type and material thickness on laser cutting performance. The methodology described in this article can be used as a guideline to calculate laser power requirements and size the laser equipment at an early stage prior to the manufacturing process.

1. Introduction

Laser cutting is an established manufacturing process for a diverse range of materials using a high-energy laser beam. The process relies on melting and evaporating the material with a continuous movement of a laser beam. The total laser power required to cut any material includes two main parts: (a) useful power, and (b) waste (non-useful) power. Useful power is the energy that directly contributes to the cutting and removal of material while waste power represents the energy loss due to heat transfer into surrounding during the laser cutting.

Useful power can be calculated analytically based on the volume of material to be melted and removed by laser while waste power requires complex numerical modelling to simulate the heat transfer into the surrounding or experimental procedure to measure the waste energy during laser processing.

Simulation is a difficult task due to the complexity of laser processes where various physical phenomena are coupled such as cutting speed, material thickness, laser power, the cut kerf shape and size, phase changes of materials and the incorporation of latent heat during melting and evaporation [1]. This article aims to develop a simple and reliable analytical model which can be used to calculate the total laser power (both useful and waste powers) that is required to cut any material, including porous media, without the need for complex numerical modelling.

Several articles have been published on heat transfer during the laser cutting of materials to understand the Heat Affected Zone (HAZ). Most studies have solved numerically the transient heat transfer equation with or without the source term accounting for laser heat input. Steen and Mazumder [2,3] described various models and solutions for modeling laser interaction including finite element and finite difference numerical solutions. Borkmann et al. [4] studied the airflow and heat transfer in the kerf by treating the kerf as a two-dimensional channel and using a simple Nusselt number correlation for studying heat transfer. Their calculations show that the heat loss is less than 6 % of the absorbed laser power.

A more advanced model based on heat balance equation between conduction and temperature rise has been considered by Wu et al. [5]. The model considers laser power but does not consider material melting

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https://doi.org/10.1016/j.ijthermalsci.2024.109513
Received 23 September 2023; Received in revised form 9 September 2024; Accepted 2 November 2024

and evaporation. The governing equation has been solved using Fourier transformation and it has been used to study the temperature distribution for different laser-cutting conditions such as scanning speed, incident angle and surface unevenness.

Choi et al. [6] studied conduction heat transfer during laser cutting for different diagonal material shapes using a transient heat conduction equation. The equation does not include the melting and evaporation of material. The effect of laser on the heat conduction has been included through the boundary conditions. Their results show that the material shape with thicker material before the slope will produce better cutting due to pre-heating and higher heat accumulation.

Cao et al. [7] used a three-dimensional (3D) transient conduction equation with a laser source term to determine the softening zone inside a ceramic rod for turning process. The equation was solved using a finite element method. Chen et al. [8] studied the heat-affected zone (HAZ) around laser cutting of a carbon fiber enforced polymer laminate using a one-dimensional heat conduction equation. The effects of melting and evaporation were incorporated via boundary temperature. This study investigated the heat damaged zone during the laser cutting.

Literature review shows that many of the heat transfer modelling studies were focused on cutting solid metals [9]. On the other hand, the present study is focused on understanding the laser cutting heat transfer in a porous media, which is filled with liquid. These types of porous materials are very common in engineering analysis such as oil and gas reservoir rocks.

Intensive laboratory work has been conducted in the past to measure the interaction of laser with rock (a type of porous media) including the early work conducted in 1971 by Carstens and Brown [10] for the purpose of mechanical rock tunnelling, Gahan et al. [11], Graves et al. [12] and Erfan et al. [13]. On the other hand, Prusa et al. [14] developed a model to calculate heat conduction losses during laser cutting of mild steel with oxygen assisted gas. The model was solved numerically, and a correlation was developed to calculate heat losses as a function of Peclet number. This correlation fits heat transfer into metals but not necessarily porous media because porosity and fluid saturation will cause significant changes to heat transfer, temperature distribution, and HAZ size during laser cutting.

Powell [15] described the energy balance theory during laser cutting including useful and waste powers. Waste power due to heat transfer into surrounding is a transient process which is complex to be calculated analytically and accordingly experimental tests were conducted to measure the conductive heat losses during laser cutting process. The energy balance equation described by Powell is used in this article as the base equation to calculate total laser power including useful and waste powers.

Yilbas et al. [16] conducted laser cutting experiments for various materials including Ti-6Al-4V alloy, steel 304, Inconel 625, and alumina to measure the variations of kerf width with cutting speed and laser power. High pressure nitrogen assisting gas was used to avoid excessive oxidation reactions. The experiments showed that increasing laser power or reducing cutting speed results in increased kerf width size.

Mostafa and Hossain [9] developed a finite difference mathematical model to simulate heat transfer into surrounding (waste power) during laser cutting. To be able to calculate the waste power analytically without the need for experimental tests or complex heat transfer numerical modelling, a new correlation has been developed in this article. Further, a modification has been made to the energy balance equation to incorporate the effect of porosity and fluid saturation existing in porous media using volumetric averaging and effective thermal properties. The model has been validated against multiple experimental tests for cutting metals and rocks and showed excellent corroboration.

The present study further extends the validated model of Mostafa and Hossain [9] to develop an analytical model that calculates waste heat during the laser cutting. This article can contribute to the laser material processing industry where total laser power required to cut any material can be calculated analytically without the needs for complex numerical modelling.

2. Methodology

Conservation of energy is the basis of laser power calculations, as it ensures that the total energy input to the laser system is accounted for in terms of various energy outputs and losses. The energy balance equation developed by Powell [15] and described by Webb and Jones [17] has been used as the base equation in the analytical model. The equation has been modified to incorporate a new waste power correlation as well as porosity and fluid saturation.

2.1. Energy balance (base equation)

It is important to note that conservation of energy considerations is crucial for understanding the performance and efficiency of a laser cutting system as well as ensuring that the laser power calculations accurately reflect the overall energy balance within the system. Here, the energy balance equation as described by Webb and Jones [17], are as follows;

Laser energy supplied to the cut zone = useful energy used in material cutting + waste energy which doesn't contribute into the process.

$$(P-b)\left[\frac{100-r_f}{100}\right] = (E_{cut}\ v\ d\ w) + [(0.5\ \pi\ d\ w)(A+B+C)] \tag{1}$$

Where P is total laser power in watts, b is laser power transmitted without interaction in watts, r_f is reflectivity of the cut zone in %, E_{cut} is specific energy in J/m^3, v is cutting speed in m/s, d is material thickness in meter, w is kerf width in meter, A is conductive loss function in W/m^2, B is radiative loss function in W/m^2, and C is convective loss function in W/m^2

The left-hand side of equation (1) describes the primary losses which include the energy losses before laser interaction with the material (b and r_f). The right-hand side describes the useful energy in addition to the secondary losses which include the energy losses after thermal transformation due to heat transfer into surrounding by conduction, convection, and radiation ($A+B+C$).

Secondary losses are the function of cutting front temperature and its surface area in contact with surrounding. It is assumed that the conductive losses originate from the convex face of the cutting front in contact with the surrounding material while convective and radiative losses come from the concave face of the cutting front in contact with the surrounding atmosphere. However, convective, and radiative losses are negligible and can be ignored.

2.2. Modified energy balance equation

After identifying the relevant energy interactions, and to accurately represent the energy conservation principles, the energy balance equation can be modified or extended to suit specific applications. Here for simplicity, it has been assumed that no light will be transmitted without interacting with material ($b = Zero$), material will fully absorb laser light ($r_f = Zero$) and radiative and convective losses are negligible (B & $C = Zero$). According to these assumptions, total laser power will comprise useful power used to melt material and waste power due to conductive heat transfer into surrounding.

It worth mentioning that the energy balance equation doesn't consider laser beam distribution and its effect on cut profile, volume of materials removed and HAZ. This is one of the limitations of the proposed analytical model. However, the aim of the model is to provide an estimated laser power required to cut a specific material thickness with an acceptable level of accuracy.

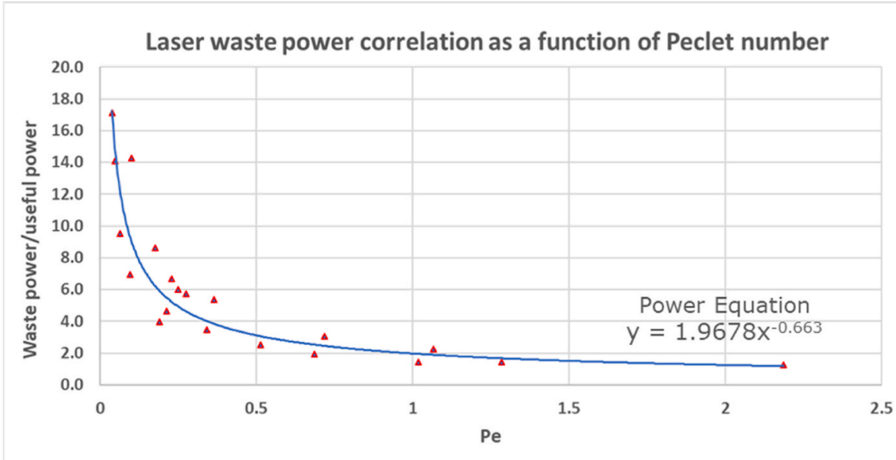

Fig. 1. Waste power correlation as a function of Peclet number.

2.2.1. Useful power

According to equation (1), useful power can be described as a function of specific energy and laser cutting geometry.

$$useful\ power = E_{cut}\ v\ d\ w \tag{2}$$

where E_{cut} is the specific energy required to melt a specific volume of material with density ρ and temperature rise ΔT.

$$E_{cut} = \rho\ c_p\ \Delta T + \rho\ L_h \tag{3}$$

Latent heat, L_h, is added to the specific energy to represent the heat energy absorbed by material during melting process (phase changing).

From equation (2) and equation (3):

$$Useful\ power = v\ d\ w\ (\rho\ c_p\ \Delta T + \rho\ L_h) \tag{4}$$

To incorporate the effect of porosity and fluid saturation exist in porous media including liquid and gas phases, the thermal properties $\rho\ c_p$ and $\rho\ L_h$ will be replaced by the effective thermal properties using a volumetric averaging approach.

$$Useful\ power = v\ d\ w\ \left(\overline{\rho c}_{peff}\ \Delta T + \overline{\rho L}_{heff}\right) \tag{5}$$

where effective thermal properties can be described as follows:

$$\overline{\rho c}_{peff} = \phi\ \left(\overline{\rho c}_{pl}\ S_l + \overline{\rho c}_{pg}\ S_g\right) + (1-\phi)\ \overline{\rho c}_{ps} \tag{6}$$

$$\overline{\rho L}_{heff} = \phi\ (\overline{\rho L}_{vl}\ S_l) + (1-\phi)\ \overline{\rho L}_{hs} \tag{7}$$

where l, g and s are subscripts for liquid, gas and solid respectively.

2.2.2. Waste power (new correlation)

Useful power is a straightforward calculation based on the volume of material to be melted while waste power due to transient heat transfer into surrounding is too complex to be calculated analytically.

The line-source numerical model developed by Mostafa and Hossain [9] to simulate laser waste power showed good corroboration with experimental data for cutting porous media and metals. To develop a simple and reliable correlation which can be used to analytically calculate laser waste power without the needs for complex numerical modelling, a correlation has been developed between waste power and useful power as a function of Peclet number as shown in Fig. 1. Peclet number represents the relationship between laser cutting property and thermal property of the material to be cut.

The correlation includes both useful and waste powers. The useful power equation proposed in this article was used to calculate the useful power component while waste power component was calculated by the numerical heat transfer model [9]. The two components were added up to calculate the total laser power, then validation with experimental data was conducted and correlation between useful and waste powers has been developed accordingly.

Waste power can fit the following correlation as a function of useful power and Peclet number:

$$\frac{P_{waste}}{P_{useful}} = 1.9678\ P_e^{-0.663} \tag{8}$$

where P_{waste} and P_{useful} are waste and useful laser power respectively and P_e is Peclet number.

In the context of laser cutting, Peclet number may be interpreted as cutting speed, or the relationship between cutting speed (advection) and kerf width (diffusion) based on the material properties. Prusa et al. [14] described Peclet number in laser cutting as following:

$$P_e = \frac{w}{2}\ v \Big/ \alpha \tag{9}$$

where w is kerf width, v is cutting speed and α is thermal diffusivity, $\alpha = k/\rho c_p$. The effect of porosity and fluid saturation can be incorporated into Peclet number by considering the effective thermal diffusivity α_{eff}:

$$\alpha_{eff} = \phi\ (\alpha_l\ S_l + \alpha_g\ S_g) + (1-\phi)\ \ \alpha_s \tag{10}$$

where l, g and s are subscripts for liquid, gas and solid respectively.

The maximum material thickness used in these experiments is 60 mm. Further experimental tests are required to confirm the validity of using this correlation for cutting thicker materials.

2.2.3. Total laser power

By adding useful power, equation (5), to waste power, equation (8), the final total laser power equation can be described as following:

$$P = v\ d\ w\ \left(\overline{\rho c}_{peff}\ \Delta T + \overline{\rho L}_{heff}\right) + \left(1 + 1.9678\ \ P_e^{-0.663}\right) \tag{11}$$

2.3. Phase changes in porous media

Understanding how phase changes occur in porous media due to laser interaction is essential for optimizing laser-based processes. Porous media is a material can contain voids or pores within their structure, which can play a significant role in how phase changes occur when subjected to laser beam. Under laser interaction, the behavior of porous media is complex and depends on multiple factors, such as laser parameters, material properties, pore size and distribution. Phase changes in porous media will occur in stages during temperature rising due to

Table 1
Phase changes in porous media during laser cutting.

Stages	Temperature range
Stage-1	$T \leq T_{v_l}$ $(T_i \rightarrow^{to} T_{v_l})$ from initial temperature to the temperature of vaporization of liquid
Stage-2	$T \geq T_{v_l}$ $(T_{v_l} \rightarrow^{to} T_{m_s})$ between the temperature of vaporization of liquid and the melting temperature of solid

laser interaction. Stage-1 represents the period between initial temperature and the temperature of vaporization of the liquid exist in pore space. Stage-2 represents the period between the temperature of vaporizations of liquid and the melting temperature of solid. Table 1 shows summary of phase change stages.

2.3.1. Temperature of vaporization and latent heat

Temperature of vaporization for liquid phase exist in pore space is required in laser power calculations to accurately represent the phase change in porous media during laser interaction.

There is an indirect relationship between the temperature of vaporization and the latent heat of vaporization (i.e., energy required to change a substance from a liquid to a vapor (gas) phase without a change in temperature). As temperature of vaporization increases towards the critical point, the latent heat of vaporization decreases. In other words, if the temperature is high and close to the critical point, less energy would be required to change the liquid phase into gas phase than the energy required at lower temperatures.

Modified Watson equation can be used to calculate the latent heat of vaporization as a function of temperature [18]:

$$L_v = A\left(1 - \frac{T}{T_c}\right)^n \tag{12}$$

where L_v is latent heat of vaporization, A and n are regression coefficient, T_c is critical temperature and T is temperature. Thermal properties including thermal conductivity and heat capacity changes with temperature. Coker [18] presented some experimental correlations which were developed to calculate the change in thermal properties as a function of temperature.

It has been observed that heat capacity of gas and liquid increases with increasing temperature, also the thermal conductivity of low-pressure gas increases with increasing temperature. Thermal conductivity of liquid and solids is generally much higher than gases. However, thermal conductivity of liquid and solids decreases with increasing temperature.

The change in the thermal properties of solids, the dominating material in heat transfer into surrounding during laser cutting, is not significant and accordingly changes of rock thermal properties with temperature has been ignored for simplicity.

3. Model validation

The model has been validated with Erfan et al. [13] experimental work conducted on carbonate rocks saturated with water and oil as well as dry samples. ND:YAG laser was applied to rock samples and specific energy was calculated under various conditions.

XRD before lasing showed 85.1 % Calcite. After lasing, Calcite mineral transformed into a combination of Calcite, Portlandite and Calcium Oxide. This causes volume and rock permeability increases. The density of water and oil used to saturate the core samples is 1.0 and 0.92 g/cc respectively.

Table 2 shows the experimental data and model validation results. The deviation (accuracy) represent the difference (comparison) between the total power calculated by the model (model results) and the total power used in the experiment (40 W).

The kerf width created during the experiment is not given. The volume of rock removed was calculated from the given total power (40 W) and specific energy (power = volume of rock removed x specific energy/radiation time). Then the calculated volume of rock removed and the given drilling depth was used to calculate the average kerf width (volume = width^2 x depth). Kerf width is one of the model input parameters and this calculations were made to define the average kerf width that matches the other given experimental data. However, model validation (accuracy) was defined by comparing the power predicted by the model and the power used in the experiment.

The model showed good corroboration with experimental data. The average deviation is approximately 10 % for water and oil saturated rock samples and around 17 % for dry samples. The reason of the high deviation for the dry samples could be the presence of irreducible water saturation unless the samples were heated up to evaporate water prior to the experiment. However, dry samples with zero water saturation assumed in the model. Also it has been observed that the level of accuracy (matching between model results and experimental data) is

Table 2
Model validation against carbonate rock.

Rock saturation	Experimental data						Calculated parameters/model results				Deviation, (difference in total power)
	Sample	Radiation time	Drilling depth	ROP	SE	Total power	Average kerf width	volume of rock removed	*Pe*	Total power	
	#	sec	mm	mm/s	KJ/cc	Watts	mm	cc		Watts	%
Water	1	5	6.01	1.20	45.38	40.00	0.86	0.00444	0.150	45.89	14.73
	2	10	8.23	0.82	66.28	40.00	0.86	0.00609	0.080	47.40	18.49
	3	15	9.2	0.61	88.94	40.00	0.86	0.00680	0.050	45.29	13.21
	4	20	9.73	0.49	112.12	40.00	0.86	0.00720	0.040	42.97	7.42
	5	25	9.92	0.40	137.47	40.00	0.86	0.00734	0.030	40.32	0.80
											AVG 10.9 %
Oil	1	5	6.61	1.32	41.26	40.00	0.86	0.00489	0.150	47.21	18.02
	2	10	8.7	0.87	62.70	40.00	0.86	0.00643	0.080	46.86	17.15
	3	15	9.82	0.65	83.32	40.00	0.86	0.00726	0.050	45.21	13.02
	4	20	10.2	0.51	106.96	40.00	0.86	0.00754	0.040	42.13	5.32
	5	25	10.51	0.42	129.75	40.00	0.86	0.00777	0.030	39.96	−0.11
											AVG 10.7 %
Dry	1	5	7.08	1.42	38.5	40.00	0.86	0.00524	0.150	50.93	27.32
	2	10	9.12	0.91	59.8	40.00	0.86	0.00675	0.080	49.48	23.69
	3	15	10.16	0.68	80.5	40.00	0.86	0.00751	0.050	47.11	17.78
	4	20	10.7	0.54	102.0	40.00	0.86	0.00791	0.040	44.51	11.28
	5	25	11.16	0.45	122.2	40.00	0.86	0.00825	0.030	42.73	6.83
											AVG 17.4 %

Table 3
Thermal properties of sandstone and limestone rocks [19].

Rock type	Specific heat capacity at constant pressure, (J/kg.K)	Thermal conductivity, (W/m. K)	Density, (kg/m^3)
Sandstone	710	1.83	2200
Limestone	900	1.30	2500

Table 4
Latent heats for sandstone and limestone rocks [20].

Rock type	Temperature of melting (T_m), °C	Temperature of vaporization (T_v), °C	Latent heat of fusion (L_f), J/kg	Latent heat of vaporization (L_v), J/kg
Sandstone	1540 (1813 K)	2200 (2473 K)	2 x 10^6	13.6 x 10^6
Limestone	1260 (1533 K)	2000 (2273 K)	1.8 x 10^6	12 x 10^6

improving with lower Peclet number.

It worth mentioning that the model can be used to simulate laser drilling as well as laser cutting. Useful power in Eq. (1) is function of the specific volume removed per unit time in m3/s which = cutting speed (m/s) x material thickness (m) x kerf width (m). The same equation can be applied to laser drilling where radiation time represents the time factor in the equation. In other word, cutting speed can be replaced by kerf width/radiation time in order to calculate the specific volume removed during laser drilling.

4. Model results and discussions

The proposed analytical model has been used to calculate the total laser power required to cut porous media under different conditions including sensitivity analyses for Peclet number, material thickness, porosity, fluid types and rock types.

4.1. Rock and fluid properties (input data)

Tables 3 and 4 show the thermal properties of sandstone and limestone rocks and Table 5 shows the thermal properties of liquids and gases used in laser power modelling.

4.2. Peclet number and temperature of vaporization

Peclet number is different at each stage and changes below and above the temperature of vaporization of the liquid exist in porous media due to the change in the effective thermal property. Peclet number for the stage below the temperature of vaporization is higher than the Peclet number above because heat capacity and density of liquid are much higher than that of gas.

However, the overall process is dominated by the stage above the temperature of vaporization of liquid in pore space because this stage is longer and requires higher energy compared to the stage below the temperature of vaporization of liquid phase. For example, according to the assumptions made in this calculations, stage-1 represents the power required to rise the temperature by only 127 K (from the initial temperature of 373 K to liquid temperature of vaporization of 500 K) while stage-2 represents the power required to rise the temperature by 1313 K (from fluid temperature of vaporization of 500 K to sandstone melting temperature of 1813 K).

The average Peclet number of the two stages (based on the temperature ratio of each stage) is very close to the Peclet number of the dominated stage above the temperature of vaporization of liquid phase (stage-2). The Peclet numbers reported in this section represent the stage above the temperature of vaporization of the liquid exists in the porous media.

4.3. Kerf width and cutting speed relationship

Equation (9) and Equation (10) were used to develop a relationship between kerf width and cutting speed as a function of Peclet number.

Table 5
Thermal properties of liquids and gas at standard condition [21].

Substance	Specific heat capacity at constant pressure, (J/kg.K)	Thermal conductivity, (W/m.K)	Latent heat of vaporization (L_v), kJ/kg
Water	4180	0.602	2257
Oil (Petroleum)	2000–3000(2500 is used as an average)	0.15	230–384(307 is used as an average)
Gas (Methane)	2180	0.031	–

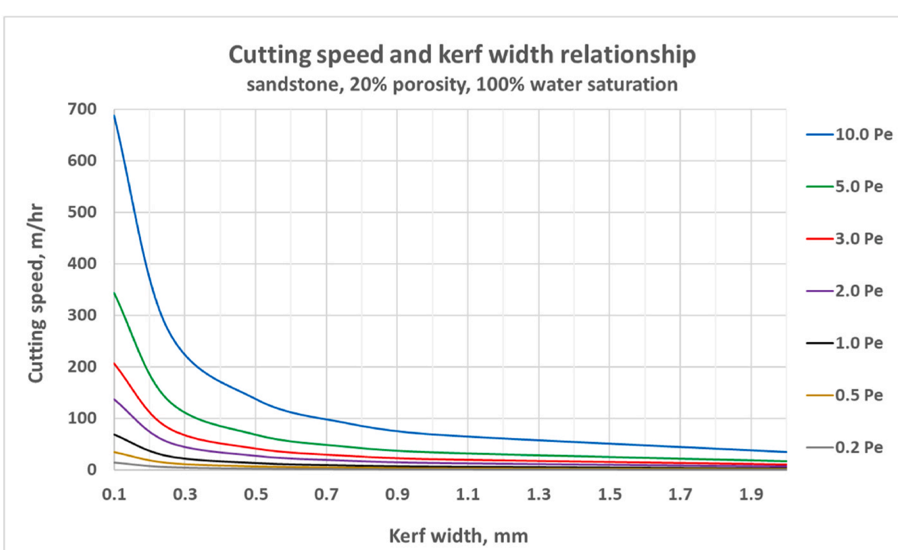

Fig. 2. Cutting speed and kerf width relationship (sandstone, 20 % porosity, 100 % water saturation).

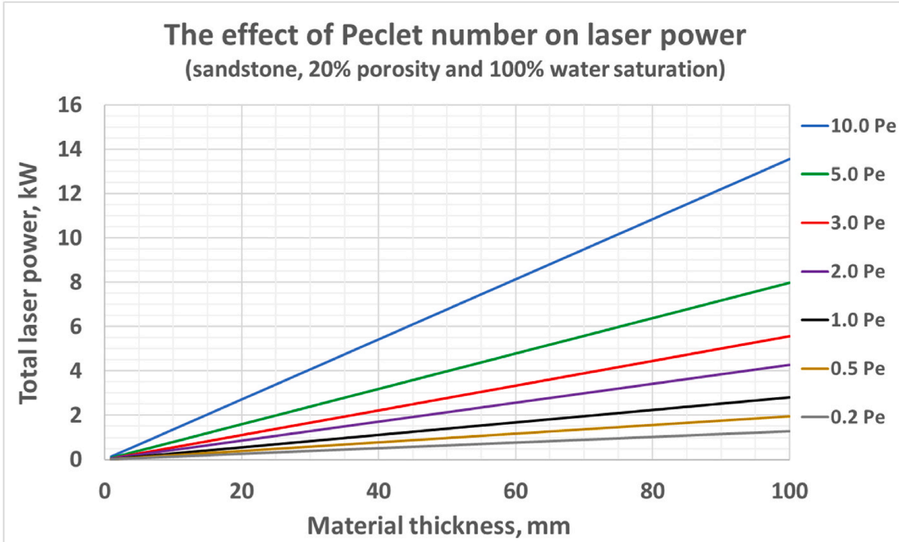

Fig. 3. The effect of Peclet number on laser power (sandstone, 20 % porosity, 100 % water saturation).

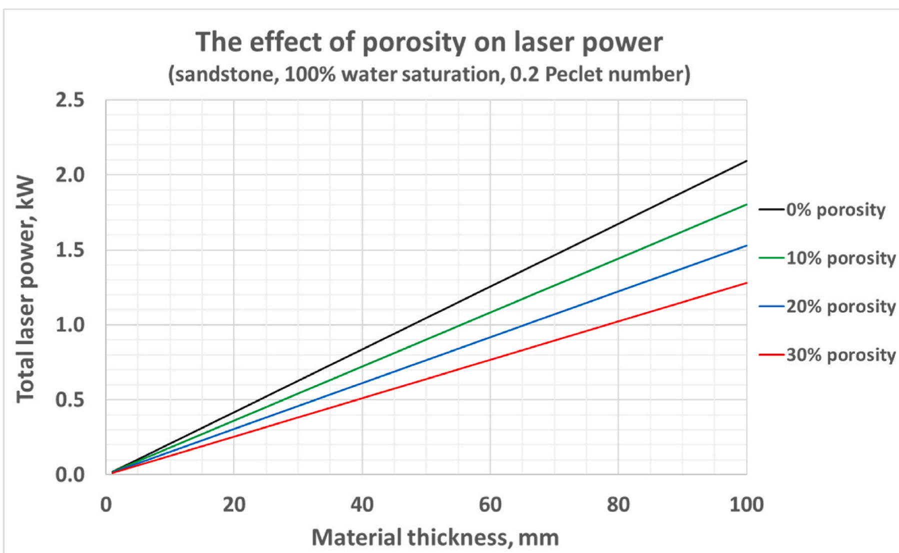

Fig. 4. The effect of porosity on laser power (sandstone, 100 % water saturation, 0.2 Peclet number).

Fig. 2 shows the results of cutting sandstone rock with 20 % porosity and 100 % water saturation. The result shows an inverse relationship between kerf width and cutting speed for cutting porous material under all Peclet numbers. Note that effective thermal diffusivity has been used to incorporate the effect of porous media and fluid saturations.

The results are consistent with the laser cutting experiments conducted by Yilbas et al. [16], where increasing laser power or reducing cutting speed results in increasing the kerf width size. At high cutting speeds, there is less time available for heating and melting materials resulting in narrower kerf and at low cutting speed, there is enough time available to heat and melt a wider kerf width.

4.4. *Peclet number and laser power*

There is a particular power required to cut a particular material thickness for each Peclet number. High laser power would be required for cutting at high Peclet number (high cutting speed or large kerf width). Equation (11) were used to define the relationship between laser power, material thickness and Peclet number. Fig. 3 shows an example of cutting sandstone by melting, 20 % porosity and 100 % water saturation. As shown, higher laser power would be required to cut the same material thickness with higher Peclet number e.g., cutting the same kerf width at higher cutting speed.

4.5. *The effect of porosity*

The laser power required to cut various thickness of sandstone rock has been calculated considering various porosity and fluid saturations. The results showed that the total laser power required to cut particular thickness decreases with increasing porosity due to the fact that the volume of rock to be melted decreases with increasing porosity and accordingly the useful power decreases. Also waste power decreases with increasing porosity because the thermal conductivity of fluids is much lower than that of rock and accordingly the heat transfer into surrounding decreases with increasing porosity.

Fig. 4 shows the total laser power required to cut sandstone by melting with various porosity (100 % water saturation and 0.2 Peclet number). As shown, the total laser power (including useful and waste

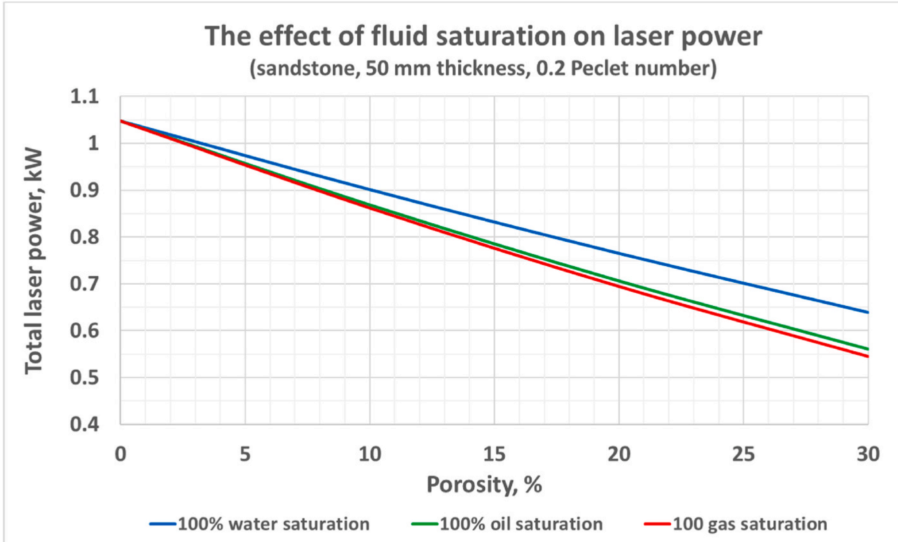

Fig. 5. The effect of fluid saturation on laser power (sandstone, 50 mm thickness, 0.2 Peclet number).

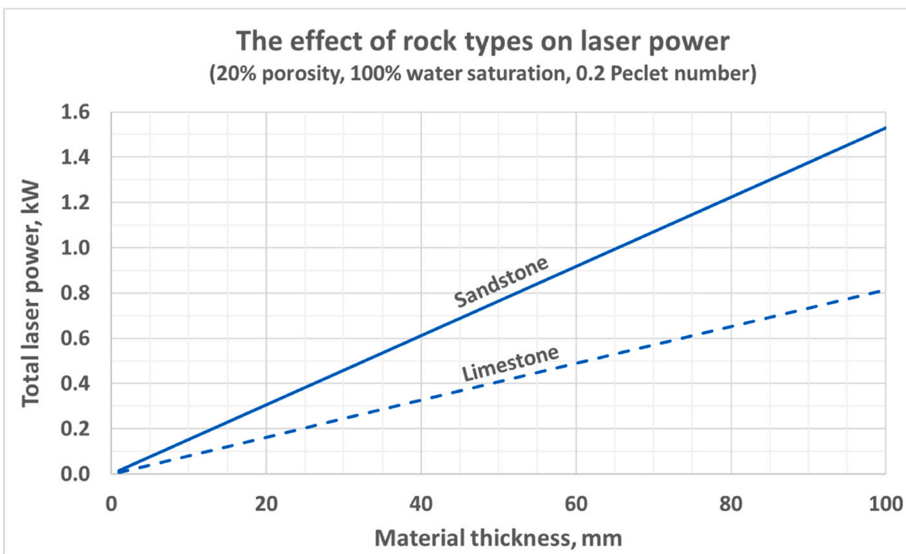

Fig. 6. The effect of rock types on laser power (20 % porosity, 100 % water saturation, 0.2 Peclet number).

powers) decreases with increasing porosity. This finding has been observed for any Peclet number and any fluid type that exists in porous media.

4.6. The effect of fluid saturation in porous media

Fig. 5 shows the effect of various fluid types on the total laser power required to cut 50 mm of sandstone by melting at 0.2 Peclet number. As shown, water requires more power compared to oil and gas and this is mainly due to the high latent heat of vaporization for water, while oil and gas are close to each other because the latent heat of vaporization for oil is low. This finding has been observed for any Peclet number and any rock thickness.

The analysis indicated that the main property which can cause the difference between various fluid types is the latent heat of vaporization while the effect of other thermal properties including heat capacity, thermal conductivity and density of fluids can cause minor difference in laser power requirement. However, the analysis showed that water evaporation consumes the highest power under all cutting conditions followed by oil then gas.

4.7. The effect of rock types

The total laser power required to cut sandstone and limestone rocks has been calculated for various material thickness and various porosity. Fig. 6 shows comparison between the total laser power required to cut sandstone and limestone at 0.2 Peclet number, 20 % porosity and 100 % water saturation.

The results showed that sandstone rock requires higher laser power than limestone rock due to the higher thermal diffusivity and melting temperature of sandstone compared to limestone.

5. Conclusions

Analytical model for laser cutting in porous media has been developed by incorporating porosity, fluid saturation and new waste power correlation into the energy balance equation. This model can be used to calculate the total laser power required to cut porous media under different cutting conditions without the needs for complex numerical models. The model has been validated with experimental data and showed good corroboration with around 10 % accuracy for fluid-saturated rock and around 17 % accuracy for dry rock.

This article can contribute into the laser material processing industry where simple and reliable analytical model has been developed and can be used at early stage to quickly size the laser equipment required prior to starting the manufacturing process.

The model is used to calculate laser power under various cutting conditions including sensitivity analyses for porosity, fluid saturation and rock type. The results showed that laser power is sensitive to rock type and porosity more than the fluid exist in porous media. Laser power significantly decreases with increasing porosity and limestone rock requires significantly lower power than sandstone. The effect of fluids types in porous media is minimal.

CRediT authorship contribution statement

Ayman Mostafa: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mamdud Hossain:** Supervision. **Nadimul Faisal:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Nomenclature:

A =: conductive loss function, W/m^2
B =: radiative loss function, W/m^2
b =: laser power transmitted without interaction, watts
C =: convective loss function, W/m^2
c_p =: specific heat capacity, J/kg.K
d =: material thickness, m
E_{cut} =: specific energy, J/m^3
k =: thermal conductivity, W/m.K
L_h =: latent heat, J/kg
L_v =: Latent heat of vaporization, kJ/mol
P =: total laser power, watts
P_e =: Peclet number, dimensionless
r_f =: reflectivity of the cut zone, %
S =: saturation, %
T =: temperature, K
T_i =: initial temperature, K
T_c =: critical temperature, K
T_v =: temperature of vaporization, K
T_m =: temperature of melting, K
v =: cutting speed, m/s
w =: kerf width, m

Greek symbols

α: is thermal diffusivity, m2/s
ρ =: density, kg/m3
ϕ =: porosity
ΔT =: temperature rise, K

Subscripts

g =: gas
l =: liquid
s =: solid