Momentum coupling at laser ablation of liquids in a porous matrix

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Abstract. The main problems at laser impact on liquids are energy dissipation and splashing, leading to poor performance even after application of special tricks like viscosity increase, thin films, cavities or droplets formation. We studied the laser ablation of liquids, including energetic ones, confined by porous matrix made of sintered titanium powder. We have compared the liquid-filled targets (ethanol, kerosene, nitromethane) momentum coupling coefficient dependency on laser fluence with the same unfilled target. Filling a porous target with a liquid may have both positive and negative effects depending on impact regime. Porous matrix prevents heat and mass losses characteristic to bulk solid and liquid targets. Momentum coupling coefficient doubled at porous target density increase by 6% only with ethanol filling, and at least tripled at ca. 22% density decrease as compared to a bulk target. Filling of porous matrices with energetic liquids leads to improvement of laser thrust generation due to combination of heat and splashing losses substantial reduction and chemical energy release.

1. Introduction
Laser plasma generation has been considered mainly for solids rather then liquids [1], since high energy density can be reached in a surface layer of the former, and plasma plume containing mainly high-speed light particles [2]. We have considered possible ways of efficiency increase at laser ablation of liquids recently; liquid media were considered because of easy desired contents preparation (properties variation) [3], well developed precise dosing (down to $10^{-15}$ L and 0.1% stability [4]) and feeding systems. The main problems at laser impact on liquids are energy dissipation [5] and droplets formation due to splashing [6], leading to poor performance [7] even after application of special tricks like viscosity increase [8], thin films [9], cavities or droplets [10] formation. Solidification (by UV curing) [11] and splashed droplets retrieval by magnetic field [12] have shown that efficient laser propulsion is possible with liquids.

Heat dissipation is restricted in porous media similar to thin films, so laser energy losses are decreased. Splashing and energy dissipation for liquids confined in pores is also suppressed. However, such target configuration has never been laser ablated before. The only work studying momentum coupling at laser ablation of liquids with porous matrices we managed to find was [13]. Liquids of 0.2 to 700 Pa*s viscosity have been considered at 10.6 μm/60 ns laser irradiation of 0.9 to 4.6 mm thick layers, so impact region was out of the 0.2 to 40 porosity medium. The latter was used as a permeable solid interface actually; its effect on momentum coupling was not investigated and is not fully used in such configuration.

Solid or liquid confining layer on either irradiated or back side (or both) of the target prevents energy losses and leads to plume compression [14]. Plume temperature rises then due to effective
absorption of laser radiation by more dense plasma and increased interaction time. Unlike flat target, in multi-layered ones, ablated medium is spread through a hole in the cover layer, in fact a nozzle is formed, so the plume is well collimated [15]. It was shown in [16, 17], that for such "exotic targets" required laser energy is reduced and momentum coupling is significantly improved. E.g., in aluminum target coated with 2 mm glass, momentum coupling coefficient increased by a factor of 12 due to detonation [18] (an increase of more than 100 was shown in [19] with an optimum shift of an order of magnitude towards lower energies).

Of all liquids, energetic ones [20, 21] are the most promising for propulsion because of energy release induced by laser irradiation. But for efficient output, those should stay compressed at high temperature. We have studied the laser ablation of liquids, including energetic ones, confined by sintered titanium powder. The aim of our study was to check if such a confinement could improve momentum coupling for a solid target, and to compare the results in terms of momentum coupling coefficient with non-impregnated Ti targets.

2. Experimental layout

The sketch of experimental setup is presented at Figure 1. We irradiated targets at ambient conditions in a single pulse mode using frequency doubled Nd:YAG laser (532 nm, 12 ns, up to 80 mJ, Lotis TII LS-2147), spot diameter at target was 224 μm. Incident laser energy was measured by control photodiode, calibrated following standard procedure, using energy meter (Ophir 30A-P-RP) placed just after lens instead of a target. Recoil momentum has been measured with a calibrated force sensor (531 mV/N, PCB Piezotronics 209C11). Electric signals were recorded by PC-coupled digital oscilloscope (Aktakom ADS-3114). Force signal was integrated over time to get recoil momentum.

The targets consisted of 0.9 mm thick porous target made of sintered titanium powder (fine gas filter manufactured by VMZ-Techno, 0.26 porosity = non-solid volume / total volume, average pore dia. 8 μm) impregnated with ethanol, kerosene or nitromethane. Liquids were supplied using a pipette until substrate saturation. To avoid target jumping, it was attached to the sensor by sticky tape.

![Figure 1. Experimental setup (a) and typical force signal (b):](image)

1 – target, 2 – force sensor, 3 – lens, 4 – control photodiode, 5 – laser, 6 – digital oscilloscope
3. Results and discussion

First, we have obtained reference data on momentum coupling for solid Ti targets: bulk, foil and porous (Figure 2a). Presence of heat transfer restrictions for the latter two has resulted in recoil momentum increase, expectedly. It’s worth mentioning, that $C_m(F)$ dependency, which represents recoil momentum normalized by laser pulse energy [22], had a quite different pattern as compared to bulk titanium target. Similarity of values obtained for all targets at high intensities can be explained by reduction of residual energy coefficient at laser fluence increase [23] and by increase of ambient air input in recoil momentum, making target properties not so important. For foil and porous targets, momentum coupling (both absolute values and dependency pattern) at low fluences were similar to polymers (which are heat insulators) [24] and metals at femtosecond laser irradiation (when heat affected zone is very small) [25]. This represents the effect of heat restriction. Although considered liquids are not heat insulators, thermal conductivity of those is still 100 times lower than for bulk titanium.

After that, we have conducted analogous measurements for porous targets impregnated by liquids (Figure 2b). The most pronounced effect was discovered for ethanol: momentum coupling coefficient doubled from its minimum and than followed the unfilled pattern. For kerosene, negative effect was observed leading to further $C_m$ decrease after unfilled minimum (almost halved), and then jump to unfilled values ($2 \times 10^{-4} \text{N}\text{s}/\text{J}$) at the edge of the studied range. Nitromethane resulted in a combination of the previous patterns: 1.5 times decrease after minimum and than jump to ethanol filled values. These patterns might be caused by heat sink to a liquid – negative effect was proportional to the heat of evaporation. Momentum coupling jump obviously happened due to exothermic reactions, fluence needed for ignition was proportional to flash temperature. However, there was no evidence of liquid detonation within porous matrix, i.e., no macroscopic destruction or other visible difference to non-filled target. Visually, it looked like combustion happened in the plume.

![Figure 2. Momentum coupling at solid (a) and filled (b) Ti targets irradiation:](image)

1 – bulk (1.5 mm), 2 – foil (0.1 mm), 3 – porous, 4 – nitromethane filled,
5 – kerosene filled, 6 – ethanol filled

So, filling a porous target with a liquid may have both positive and negative effects depending on impact regime. Any way, porous matrix prevents heat and mass losses characteristic to bulk solid and liquid targets. $C_m$ doubled at porous target density increase by 6% only with ethanol filling, and at least tripled at ca. 22% density decrease as compared to a bulk target. These relations mean that specific impulse might also increase in both cases, but it could not be stated for sure without target
weighing. We did not weigh targets to evaluate mass loss because liquid evaporation rate could not be estimated properly. To answer this question closed pores targets filled with liquids or laminated open pored ones are needed. Full confinement in such pores is close to the conditions in multi-layered targets [15], so the effect might be even more pronounced. However, manufacturing of such targets is rather complicated, at least of metal ones.

4. Conclusions
Filling of porous matrices with energetic liquids leads to improvement of laser thrust generation due to combination of heat and splashing losses substantial reduction and chemical energy release. However, heat of evaporation and flash temperature of the filling liquid should be considered, and possibly decreased for better effect. Porous targets could be easily manufactured countinously by sintering (e.g., by laser), and powder supply system can be similar to liquid. For magnetise powders, special supstrates and porous layer recovery could be used. In high performance pulsed periodic plasma generators refilling of pores with a liquid could be enhanced by ultrasound, electroosmosis and other effects. Impact on targets with energetic liquid filled closed pores could lead to even greater effect due to pressure increase.

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