

Controlling break-up of a liquid filament: from edge melting to thermal scissors

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We consider a fluid filament on a solid substrate, exposed to localised perturbations that modify its material properties, particularly its viscosity. The considered model geometry and material parameters are motivated by an experimental set-up involving metal filaments subjected to laser heating, which liquefies them, leading to fluid flow while the temperature is above the melting point. The localised perturbations are created by adding disjoint metal pillars, which, due to the effect of ‘thermal crowding’ – meaning increased energy absorption due to the additional deposited metal – modify the local filament properties. Depending on the pillars’ positioning, one could consider them either as ‘thermal scissors’ (splitting the filament at the pillar location into segments) or as the source of the filament’s edge melting, leading to retraction and break-up. A precise understanding of the mechanism underlying the filament’s break-up, supported by efficient simulations, enables rationalising the dynamics and final pattern formation, as well as controlling the size and positioning of the resulting metal particles. In particular, we identify numerically a bifurcation structure in which the positioning and number of pillars lead to a dramatic transition in the final outcome. While we focus on a rather specific set-up, we expect similar mechanisms to be relevant to other systems in which material parameters could be locally modified by externally imposed perturbations.

Key words: thin films, lubrication theory, nonlinear instability

1. Introduction

The ability to control free surface fluid film instability and the resulting pattern formation is important for numerous applications. Metal structures at the nanoscale are of particular

interest across multiple applications, such as solar cell manufacturing (Garnett *et al.* 2011; Makarov *et al.* 2016), where it is desirable to produce metal particles of a specific size and density deposited on solid substrates. While such an outcome can be achieved using lithographic techniques, these are slow and expensive. It is therefore of interest to devise bottom-up approaches that utilise natural fluid instabilities to obtain patterns with desired properties.

Liquid metals (liquefied by applied laser pulses, as in pulsed laser-induced dewetting) have been extensively explored through experimental and theoretical models of varying complexity, as reviewed by Kondic *et al.* (2020). Modelling such systems is rather involved, due to the strong coupling of fluid and thermal physics. It is worth emphasising one crucial aspect that makes modelling the described problem particularly demanding: heat absorption in the metal is volumetric, with the absorption length typically of the same order as the metal thickness (tens of nanometres). Therefore, for example, thicker metal layers can absorb more energy and thus may reach higher temperatures. Such effects, however, are limited by heat capacity, since larger metal volumes require more energy to reach elevated temperatures. The result is that for prescribed laser heating, there is an optimal metal thickness that yields the highest temperatures. Furthermore, the presence of additional metal on a substrate increases energy absorption. Since adjacent (possibly disjoint) metal structures may also communicate thermally via the underlying substrate, they may influence each other's dynamics. This effect, which we called 'thermal crowding' in our previous work (Allaire, Cummings & Kondic 2024), leads to fluid dynamics that is modified by the presence of proximal metal structures. In the present work, we show that by carefully choosing initial metal geometries, one can effectively produce localised perturbations that (again locally) modify the temperature of the surrounding metal. Since the material parameters, particularly viscosity, depend strongly on temperature, fluid properties may exhibit significant spatial variation. We show that such a set-up can be used either to effectively cut a liquid filament into multiple parts, whose sizes can be controlled, or to melt a filament from its edges and control its evolution via edge melting.

The geometry that we consider is motivated by experiments on thin SiO₂ membranes (Diez *et al.* 2021). While this particular set-up is not crucial, it simplifies modelling and computation by allowing the use of reduced asymptotic long-wave models for both fluid and thermal problems, developed in our earlier work (Allaire, Cummings & Kondic 2021). We can then carry out efficient, large-scale simulations of the resulting model, and analyse in detail the mechanisms responsible for instabilities and resulting pattern formation. Consideration of both spatial and temporal variations in metal material parameters is crucial, as they play a key role in the development of instability.

The rest of this paper is structured as follows. In § 2, we formulate the long-wave model that describes the temperature and evolution of the metal. Section 3 outlines the numerical method used to carry out the model simulations, then § 4 contains the main results, showing the influence of pillar placement on the nearby filament. Supplementary materials include an extensive set of supplementary figures and animations that are particularly useful for understanding the details of fluid evolution are available at <https://doi.org/10.1017/jfm.2026.11683>. We conclude the main text with a discussion in § 5.

2. Model

2.1. Model overview

Consider a free surface metal filament of characteristic nanoscale thickness (height) $H = 10$ nm, length $1\text{ }\mu\text{m}$, and width 40 nm, surrounded by nanopillars of identical height H and

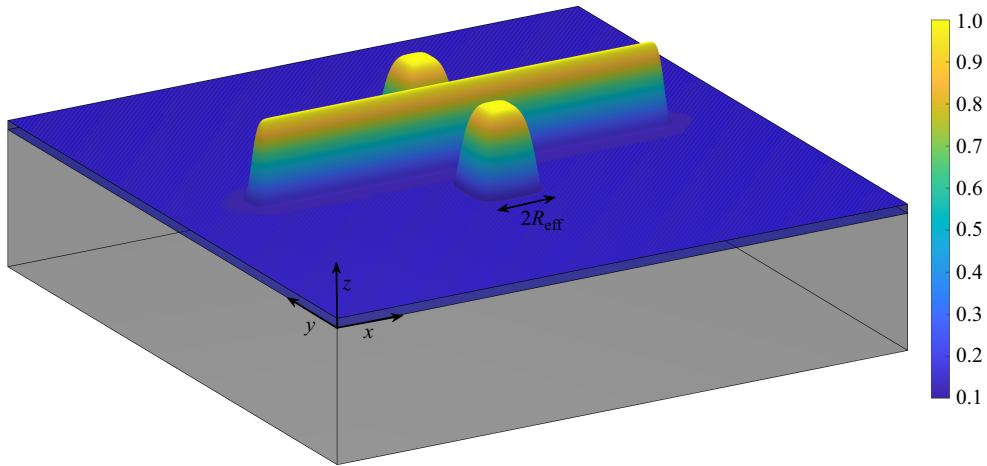


Figure 1. Schematic of a filament surrounded by two pillars. The blue region indicates the prewetted layer, and the grey region represents the underlying SiO₂ substrate. The thickness, shown by the colour bar, is non-dimensional; the length scale used throughout is $H = 10$ nm.

shape parameter R (comparable to H), which we call the pillar radius. The assembly is placed on a thermally conductive SiO₂ substrate of depth $H_s = 15$ nm; such thin substrates are often referred to as membranes (McKeown *et al.* 2015; Diez *et al.* 2021). In an effort to capture the phase transformations that occur during pulsed laser-induced dewetting while maintaining model simplicity, we assume that the metal (both filament and pillars) is initially solid, heated directly by an external laser heat source (of a spatial extent that is large compared to the domain size shown in figure 1 as in the experiments; see e.g. Kondic *et al.* 2020), and once in the liquid state, moves according to incompressible Newtonian fluid mechanics. The underlying substrate is largely optically transparent, and assumed to be heated only indirectly through thermal conduction across the metal–substrate interface. The free surface of the metal, which is exposed to air above, is denoted by $z = h(x, y, t)$, where x and y represent the in-plane coordinates, and z is the out-of-plane coordinate.

Following Allaire *et al.* (2024) we use H as a characteristic length scale, and $U = \gamma_f / (3\mu_f)$ as the velocity scale (where γ_f and μ_f are the surface tension and viscosity of the metal at melting temperature T_{melt}), which gives the time scale as $t_{scl} = H/U = 3H\mu_f/\gamma_f$. The pressure, temperature and surface tension scales are given by $\mu_f U/H$, T_{melt} and γ_f , respectively. The lateral domain considered is $0 \leq x, y \leq P$, where $P = 140$ dimensionless units (corresponding to $1.4 \mu\text{m}$). In figure 1, we show a typical initial condition, used in our simulations described later, to illustrate the geometry: a metal filament surrounded by two symmetrically placed nanopillars. Conservation of mass, momentum and energy underpins the model, which comprises Navier–Stokes equations for the flow of the molten metal, coupled to heat equations for the metal and substrate, and associated boundary and initial conditions. The model incorporates constitutive equations for material parameters that, in general, depend on the state variables, as we now discuss.

With regard to the metal parameters, we assume that the viscosity depends on temperature, whereas the surface tension, density, heat capacity and thermal conductivity are fixed at their respective melting temperature values. These assumptions are motivated by the fact that for molten copper (and comparable metals), over the temperature range considered, viscosity varies by several orders of magnitude, whereas the other material properties vary more moderately (Gale & Totemeier 2004). Concerning phase change, we note that the latent heat of melting of the metal is negligible compared to the total laser

energy supplied in the present context (see also Allaire *et al.* (2021) and the discussion following (2.6) below), thus we neglect it and assume that phase change occurs at the melting temperature, controlled by the viscosity. Before melting, the metal's viscosity is high enough to prevent fluid motion. As the metal exceeds melting temperature, the viscosity is sharply decreased, allowing the fluid to evolve. This differs slightly from our previous work (Allaire, Cummings & Kondic 2022), in that the phase transition is smooth rather than sharp. As the temperature decreases towards the melting temperature, the viscosity increases, progressively suppressing fluid motion.

In addition, surface tension gradients, both thermally driven (thermocapillary/Marangoni effects; e.g. Oron, Davis & Bankoff 1997; Shklyaev, Alabuzhev & Khenner 2012) and concentration-driven (e.g. Baumgartner *et al.* 2022; Constante-Amores *et al.* 2022), can, in principle, influence the liquid filament break-up process in set-ups such as these. However, in our previous work (Allaire *et al.* 2021), we showed that the influence of surface tension gradients is small compared to the effect of temperature-dependent viscosity on the evolution of the metal. Therefore, we omit Marangoni effects in the present setting.

Concerning the SiO₂ substrate, this material has a low thermal conductivity and high heat capacity, so heat diffusion into it is slow, and it experiences minimal thermal expansion (Hench & West 1980). Therefore, similarly to the approach used by Trice *et al.* (2007), we assume that the density, thermal conductivity and heat capacity of the substrate maintain the values that they have at room temperature T_a . Although the most high-fidelity thermal modelling should account for the temperature variation of these parameters, we consider these modelling assumptions to be sufficient for capturing the dominant physics of the system.

2.2. Model equations and boundary conditions

In our recent work (Allaire *et al.* 2024) – see also Atena & Khenner (2009) and Saeki, Fukui & Matsuoka (2013) for earlier works on this subject – we developed a model for a similar set-up with adjacent filaments under a long-wave formulation that greatly simplifies the underlying equations while retaining the most important physics as outlined above; we utilise that model here. Due to the thin film geometry, heat transfer in the out-of-plane direction occurs much faster than in the in-plane direction; coupled with the fact that the thermal conductivity in the metal is much higher than that in the underlying substrate, this means that heat loss to the substrate is relatively slow, giving a thermal field that (to leading order in the film aspect ratio) is uniform in the z -direction within the metal film: $T_f(x, y, t)$. Examining the thermal problem at the next asymptotic order leads to a solvability condition that provides a partial differential equation for $T_f(x, y, t)$. In the substrate (which is assumed perfectly insulated below), both in-plane and out-of-plane heat transfer may be relevant, and we assume that heat is lost primarily through the lateral boundaries, with perfect thermal contact between the metal and the substrate. The corresponding equations governing the temperatures T_f, T_s in both film and substrate are then

$$hPe_f \partial_t T_f = \nabla_2 \cdot (h \nabla_2 T_f) - \mathcal{K} \partial_z T_s|_{z=0} + h\bar{Q}, \quad z \in (0, h), \quad (2.1)$$

$$Pe_s \partial_t T_s = \nabla_2^2 T_s + \partial_z^2 T_s, \quad z \in (-H_s, 0), \quad (2.2)$$

where the dimensionless parameters

$$Pe_f = \frac{(\rho c)_f UH}{k_f}, \quad Pe_s = \frac{(\rho c)_s UH}{k_s}, \quad \mathcal{K} = \frac{k_s}{k_f} \quad (2.3)$$

Parameter	Notation	Value	Units
Length scale	H	10	nm
Mean filament thickness	$h_0 H$	10	nm
Filament width	$w H$	40	nm
Equilibrium film thickness	$h_* H$	1	nm
SiO ₂ thickness	$H_s H$ [A22]	15	nm
Viscosity at T_{melt}	μ_f [DK16]	4.3×10^{-3}	Pa s
Surface tension at T_{melt}	γ_f [DK16]	1.303	J m ⁻²
Fluid density	ρ_f [DK16]	8000	kg m ⁻³
Fluid specific heat capacity	c_f [DK16]	495	J kg ⁻¹ K ⁻¹
Fluid heat conductivity	k_f [DK16]	340	W m ⁻¹ K ⁻¹
SiO ₂ density	ρ_s [DK16]	2200	kg m ⁻³
SiO ₂ specific heat capacity	c_s [DK16]	937	J kg ⁻¹ K ⁻¹
SiO ₂ heat conductivity	k_s [A22]	1.4	W m ⁻¹ K ⁻¹
Hamaker constant	A_H [G13]	3.49×10^{-17}	J
Disjoining pressure exponents	(n, m)	(3, 2)	1
Laser energy density	E_0 [A24]	6800	J m ⁻²
Gaussian pulse peak time	$t_p t_{scl}$ [A24]	12	ns
Gaussian pulse width	$\sigma t_{scl} = t_p / (2\sqrt{2} \ln 2)$	5.1	ns
Reflective coefficient	r_0 [DK16]	0.3655	1
Fluid absorption length	$\alpha_f^{-1} H$ [DK16]	11.09	nm
Fluid reflective length	$\alpha_r^{-1} H$ [DK16]	12.0	nm
Melting temperature	T_{melt}	1358	K
Room temperature	$T_a T_{melt}$	300	K
Temperature coefficient of surface tension	γ_T [DK16]	-0.23×10^{-3}	J m ⁻² K ⁻¹
Activation energy	E [GT04]	30.5	kJ mol ⁻¹
Characteristic velocity	$U = H / t_{scl}$	111.11	m s ⁻¹
Time scale	$t_{scl} = 3H\mu_f / \gamma_f$	0.09	ns
Dimensionless numbers			
	Notation	Value	Expression
Fluid Péclet number	Pe_f	1.29×10^{-2}	$(\rho c)_f U H / k_f$
Substrate Péclet number	Pe_s	1.64	$(\rho c)_s U H / k_s$
Thermal conductivity ratio	$\mathcal{K}$	0.004	k_s / k_f
Dimensionless activation energy	$\mathcal{E}$	186.74	$E / (RT_{melt})$

Table 1. Parameters used for the simulations based on Cu filament/pillars and an SiO₂ substrate. The references are [DK16] Dong & Kondic (2016), [A24] Allaire *et al.* (2024), [A22] Allaire *et al.* (2022), [G13] González *et al.* (2013), and [GT04] Gale & Totemeier (2004).

represent the fluid and substrate Péclet numbers, and thermal conductivity ratio, respectively, and $\nabla_2 = (\partial_x, \partial_y, 0)$ is the in-plane gradient. The values of the parameters, assigned in accordance with relevant experimental literature, are given in table 1 (see Allaire *et al.* (2021) for further discussion of their influence). Note that as presented here, the model uses scalings different to those of Allaire *et al.* (2021); specifically, for convenience and simplicity in presentation of our results, we use just a single length scale H for lateral and transverse lengths.

The terms on the right-hand side of (2.1) (the governing equation for the metal film temperature), from left to right, represent in-plane diffusion, heat losses to the underlying membrane substrate, and depth-averaged laser heating as specified in (2.4) below. Equation (2.2) governs the substrate temperature field, where both in-plane and out-of-plane heat conduction are retained to leading order, but the laser heating is neglected on the assumption that SiO₂ is optically transparent (Allaire *et al.* 2024).

At the liquid–solid boundary $z = 0$, we assume continuity of temperatures $T_f = T_s$ (equivalent to perfect thermal contact). We represent both the lateral boundaries of the metal film, and the bottom of the SiO₂ membrane substrate, by insulating boundary conditions: $\partial_x T_f = 0$ at $x = 0, P$, $\partial_y T_f = 0$ at $y = 0, P$, and $\partial_z T = 0$ at $z = -H_s$, where the last condition models the exposure of the underlying membrane to vacuum below. The lateral ends of the membrane substrate are fixed at ambient temperature $T_s = T_a$ at $x = 0, P$ and $y = 0, P$, representing the only net heat loss mechanism of the system. The depth-averaged heat source is assumed to be supplied as a single laser pulse, given by

$$\overline{Q} = \frac{A(h)}{h} \int_0^h F(t) [1 - R(h)] \exp[-\alpha_f (h - z)] dz, \quad (2.4)$$

where α_f^{-1} is the absorption length, and $F(t)$ captures the temporal dependence of the pulse, taken to be Gaussian with centre t_p and of width $\sigma = t_p / (2\sqrt{2 \ln 2})$ (of the order of a few nanoseconds). Rather than using Maxwell's equations to determine the reflectivity of the fluid (Heavens 1955), we follow the simplified approach adopted by others (Trice *et al.* 2007; Seric, Afkhami & Kondic 2018), in which it is approximated at normal incidence as $R(h) = r_0(1 - \exp(-\alpha_r h))$, with optimised fitting parameters r_0 and α_r . All parameter values are provided in table 1. To eliminate heat absorption in the prewetted region of thickness h_* (present for numerical and modelling convenience, and discussed below), we choose $A(h)$ to be a smooth approximation of $\mathcal{U}(h - h_*)$, the unit step function centred at h_* .

To summarise, the evolution of the metal film, modelled using a long-wave approach, is described by the fourth-order partial differential equation (Allaire *et al.* 2021)

$$\partial_t h + \nabla_2 \cdot \left[\frac{1}{\mu(T_f)} h^3 \nabla_2 \left(\nabla_2^2 h + \Pi(h) \right) \right] = 0, \quad (2.5)$$

where the first and second terms following the time derivative represent capillary (modelling surface tension) and disjoining pressure (modelling small-scale liquid–solid interactions, discussed further below) effects. The viscosity $\mu(T_f)$ is assumed to have Arrhenius-type temperature dependence,

$$\mu(T_f) = S(T_f) \exp \left(\mathcal{E} \left(\frac{1}{T_f} - 1 \right) \right), \quad (2.6)$$

where the dimensionless number $\mathcal{E} = E / (R_{gas} T_{melt})$ depends on the activation energy E and the universal gas constant R_{gas} (Gale & Totemeier 2004). The sigmoid function $S(T_f) = 2(\tanh((T_f - 1) + \delta_T) + 1)^{-1}$ approximates the solid–liquid phase transition, with $\delta_T = (5 \text{ K}) / T_{melt} \ll 1$; since μ varies in space and time, this approach permits localised melting/solidification. Note that this viscosity model is a simplified representation of the phase transition, rather than a precise one that uses a latent heat. In our previous work (Allaire *et al.* 2022), we have argued that the latent energy of melting is negligible compared to the total energy supplied by the laser, consistent with the modelling by Trice *et al.* (2007), which incorporates a latent heat. Therefore, we consider our viscosity-based representation of phase change sufficient for our purposes.

Although various forms of disjoining pressure have been used (and particularly in the case of metals, the relevant physics becomes very involved; see Kondic *et al.* (2020) for a brief overview), we follow the approach taken by González *et al.* (2013) that uses a simple

power law with conjoining and disjoining forces,

$$\Pi(h) = \Omega \left[\left(\frac{h}{h_*} \right)^3 - \left(\frac{h}{h_*} \right)^2 \right], \quad (2.7)$$

where the dimensionless parameter Ω is related to the Hamaker constant A_H by $\Omega = A_H / (6\pi\gamma_f h_*^3 H^2)$. This form ensures that the film height does not fall below the equilibrium film thickness h_* ; in the present work, we use $h_* = 0.1$, corresponding to 1 nm. We note that when film instability is considered, the value of h_* is relevant when comparing theoretical results with experimental ones; see González *et al.* (2013) for an extensive discussion in the context of dewetting metal films. However, when considering filaments (as in the present work), the evolution is governed primarily by capillary and viscous forces, therefore the exact value of h_* is not relevant; see Diez, González & Kondic (2009) for a discussion of this point. We also re-emphasise that our model treats the metal as a Newtonian fluid, thus cannot account for effects related to non-Newtonian behaviour, or possible crystallisation that may lead to contact line pinning. Despite these simplifications, based on qualitative and sometimes even quantitative agreement between theoretical and experimental results reported in our earlier works (Kondic *et al.* 2009; Fowlkes *et al.* 2011; Wu *et al.* 2011), we expect that the model that we implement is a reasonable approximation. We note in particular that modelling contact line pinning is not straightforward within the present long-wave-based formulation; theoretical efforts in this direction are limited (Beltrame & Thiele 2010; Lin *et al.* 2016), and more work is needed to include such effects, in particular in the context of liquid metals on the nanoscale.

2.3. Initial conditions

Following our previous work (Allaire *et al.* 2024), the initial condition of the filament is given by a combination of smooth tanh functions

$$\mathcal{F}(x, y) = h_* + A_0 (\tanh(x - x_1) \tanh(x_2 - x) + 1) (\tanh(y - y_1) \tanh(y_2 - y) + 1), \quad (2.8)$$

where $x_1 = 20$, $x_2 = 120$, $y_1 = 68$, $y_2 = 72$, making the filament of approximate length and width equal to 100 and 4 dimensionless units, respectively. We can also specify an arbitrary collection of N pillars as follows. We denote the k th pillar by B_k , represented by a modified bump function, and the linear combination of the N pillars by $P(x, y)$, as

$$\begin{aligned} P(x, y) &= \sum_{k=1}^N \beta_k B_k(x, y), \\ B_k(x, y) &= \begin{cases} \exp\left(-\frac{1}{R - r_k(x, y)}\right), & r_k(x, y) < R, \\ 0, & r_k(x, y) > R, \end{cases} \\ r_k(x, y) &= a_x(x - x_k)^4 + a_y(y - y_k)^4, \end{aligned} \quad (2.9)$$

where $a_x = a_y = 10^{-3}$, (x_k, y_k) is the location of the k th pillar centre, and β_k are chosen so that each pillar has height 1 (after shifting up by the prewetted film thickness).

In simulations, we can choose how many pillars, N , to include, ensuring that they do not overlap each other or the filament. The pillar footprint $r_k = R$ is known as a ‘squire’ of effective radius $R_{eff} = (R/a_x)^{1/4} = (R/a_y)^{1/4}$; for simplicity of presentation, we choose to call R the pillar radius. This representation of pillars was chosen over the classical bump function to better align with the Cartesian grid used in simulations. The combined initial

condition is then given by $h(x, y, 0) = \mathcal{F}(x, y) + P(x, y)$. The depiction of the initial condition in figure 1 shows a case with $N = 2$.

For simplicity, we consider only pillars of the prescribed shape given here. While different geometries may influence transient heating through variations in surface area and laser energy absorption, once molten, the pillars rapidly retract in order to minimise their surface area. This relaxation occurs on a time scale faster than the underlying filament's instability development. Therefore, the chosen pillar geometry is expected to lead to behaviour that is representative of that achieved with other pillars of comparable volume.

3. Numerical method

Following our previous work (Allaire *et al.* 2022), we use a finite-difference-based approach to numerically solve (2.1), (2.2) and (2.5) with a uniform spatial resolution $\Delta x = \Delta y = h_* = 0.1$. Equation (2.5) can be rewritten in the general conservation form $\partial_t h + \nabla \cdot \mathbf{F}(h) = 0$, where $\mathbf{F}$ is the flux. We adopt the cell-centred approach of Lam, Cummings & Kondic (2018), which approximates the divergence using the flux at the cell walls, thereby conserving mass. Time integration is performed using the trapezoidal rule (effectively a Crank–Nicolson scheme), which, due to nonlinearity, leads to a root-finding problem $\mathbf{G}(\mathbf{h}^{n+1}) = \mathbf{0}$, where $\mathbf{h}^{n+1}$ is the vector of fluid thickness values on the spatial grid at the future time-step t_{n+1} . The nonlinear system is solved with Newton's method. To reduce computational cost, the alternating-direction-implicit (ADI) method is used to split the Jacobian into its one-dimensional counterparts, reducing the underlying problem to solving multiple pentadiagonal linear systems, which are solved in parallel on graphics processing units (GPUs) using CUDA. For a detailed exposition of the thin film equation solver, the reader is referred to Lam *et al.* (2018).

To numerically solve (2.1), we use the implicit–explicit scheme, detailed in the appendix of our previous work (Allaire *et al.* 2022), that combines a Runge–Kutta order-2 (RK2) method on the heat sink term, $\mathcal{K} \partial_z T_s|_{z=0}$, with the classical Peaceman–Rachford ADI method on the remaining terms. This hybrid method ensures second-order accuracy in space and time; even though the predictor–corrector RK2 requires more computations per time step, many terms do not need to be recomputed in the correction phase. Using the algorithm in an $N \times M$ computational grid leads to solving M linear systems of size N , followed by N linear systems of size M , all tridiagonal. Each of these is solved in parallel on the GPU using a sparse solver (in this case the Thomas algorithm).

Since (2.2) is a three-dimensional linear diffusion equation, we utilise the Douglas–Gunn ADI method, which is second-order accurate in both space and time. The fluid (metal) shape is initialised as $h(x, y, 0) = \mathcal{F}(x, y) + P(x, y)$, given above, and both the metal and substrate temperatures are initially fixed at room temperature:

$$T_f(x, y, 0) = T_s(x, y, 0) = T_a. \quad (2.10)$$

Successful time integration requires that (i) the iterative Newton's method converges to a relative error tolerance of 10^{-9} , and (ii) the relative truncation error in both fluid evolution and heating is less than 10^{-3} . If either of these fails, then the time step is decreased and the step is restarted.

4. Results

We now present our main results for simulations of simple metal structures exposed to laser heating on an SiO₂ membrane substrate. We begin with a detailed study of a single

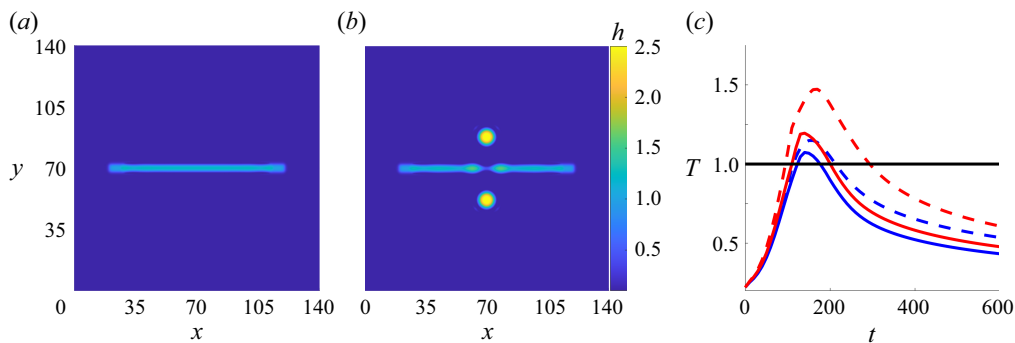


Figure 2. Final thickness of (a) a filament alone, and (b) a filament surrounded by equally spaced pillars, indicating the effect of additional heating. The average (blue) and maximum (red) filament temperatures for (a) and (b) are given in (c) as solid and dashed lines, respectively. The melting temperature is given by the solid black line. Here, the pillar–filament distance (between pillar centre and filament long axis) is $D = 15$, and the pillar radius is $R = 6$. Length, time and temperature are scaled by 10 nm, 0.09 ns and 1358 K, respectively.

metal filament with two adjacent pillars in § 4.1, then present a preliminary investigation of a filament with four surrounding pillars in § 4.2.

4.1. Effect of two adjacent pillars on filament evolution

We first illustrate the effect of pillars on metal filament evolution for a simple geometry in which two pillars are symmetrically positioned, with their centres on the line of symmetry perpendicular to the filament axis, as shown in figure 1. Figure 2 shows the outcome both with (figure 2a) and without (figure 2b) pillars; the dynamic evolution is provided in supplementary movie 1. The influence of the pillars can be understood by considering the filament temperature (figure 2c). We define the average filament temperature to be

$$T_{\text{avg}}(t) = \frac{\int_0^P \int_0^P \chi_{\text{fil}} A(h) T_f \, dx \, dy}{\int_0^P \int_0^P \chi_{\text{fil}} A(h) \, dx \, dy}, \quad (3.1)$$

which is a spatially weighted average of the fluid temperature restricted to the filament region, as determined by the indicator function χ_{fil} . The smooth activation function $A(h)$, defined in (2.4), smoothly suppresses contributions from regions of sufficiently low thickness. Both average and maximum temperatures of the filament are shown, and both are higher when pillars are present. This higher temperature leads to decreased viscosity and therefore faster evolution. As a consequence, the filament evolution with pillars present proceeds further before solidification, and filament break-up occurs.

We note that the filament is not externally perturbed, so the break-up (for figure 2b) must be due to amplification of numerical noise. While the instability process by which a finite-length filament deposited on a solid substrate breaks up is a complicated problem (see the extensive discussion in Diez *et al.* 2009), for our dual purposes of understanding the fundamentals of the filament break-up and to confirm that numerical noise is a rational explanation for it, we may simplify the discussion by: (i) ignoring finite filament length, which is irrelevant if the filament's ends are far away from the break-up location; and (ii) realising that basic understanding can be reached by assuming that the problem is similar to that of a free-standing infinite-length filament subject to a Rayleigh–Plateau (RP) type instability. (For simplicity, in the present paper we will refer to instability leading to

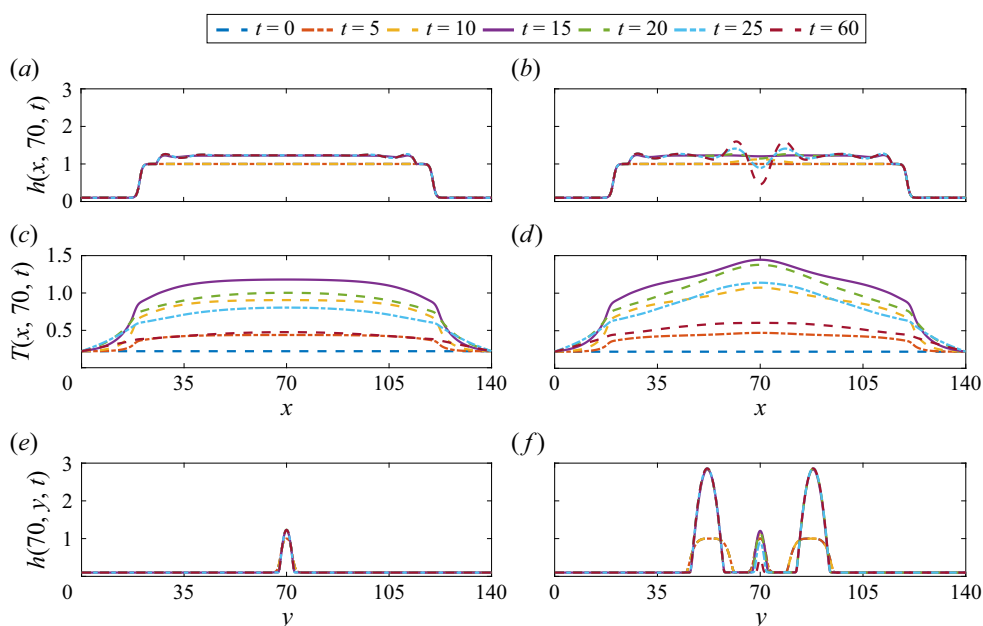


Figure 3. Horizontal slices (along the filament long axis) of (a,b) filament thickness and (c,d) temperature field, and (e,f) vertical slices (perpendicular to the filament long axis) of filament (and pillar) thickness, at times $t = 0, 5, 10, 15, 20, 25, 60$ as listed in the legend, for (a,c,e) the single filament in figure 2(a), and (b,d,f) the filament with surrounding pillars in figure 2(b).

break-up of a filament deposited on a substrate that is not influenced by finite-length effects as RP break-up or RP mechanism.) The classical RP results specify that the maximum growth rate of small perturbations of a fluid filament of (dimensional) radius r_f is of the order of $\omega = \gamma_f / (\mu_f r_f)$. To obtain an order-of-magnitude estimate, we use the values of the material parameters at melting temperature (see table 1), take r_f to be the filament half-width, and assume that the numerical noise is at the level $A_0 \sim 10^{-12}$ (as expected for simulations carried out using double-precision arithmetic). Furthermore, assuming that the linear stability approximation extends well into the nonlinear regime, so that a perturbation of amplitude A_0 grows according to $A \approx A_0 \exp[(\omega t_{sc})t]$ (note that ω is dimensional, so we multiply by the chosen time scale t_{sc} ; see table 1), we find that the approximate non-dimensional break-up time is ≈ 30 time units. The results shown in figure 2 are consistent with this order-of-magnitude estimate, with the time period during which the temperature is above the melting value for a filament without pillars not being long enough for instability to develop. (Note that our back-of-an-envelope estimate above underestimates the break-up time, since the growth of a perturbation is typically slower than exponential during nonlinear stages of evolution.)

Figure 3 provides more precise information about the filament evolution, showing the results for both filament thickness and temperature, along cross-sections that illustrate the influence of the presence of pillars. Although the difference in the temperatures along the filament axis is not dramatic (compare figures 3c,d), it is sufficient to lead to significantly different thickness evolution, due to the strong dependence of filament viscosity on temperature.

Having illustrated the basic features of filament instability development with and without pillars, we now discuss the parametric dependence – in particular, the level of control achievable, and the different instability mechanisms.

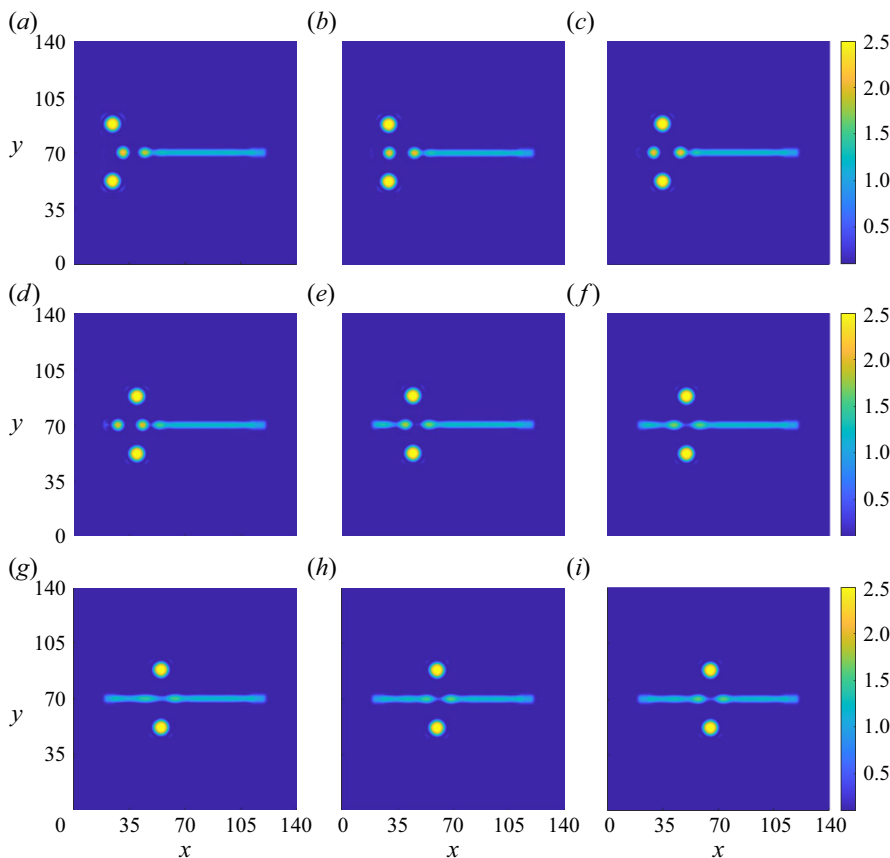


Figure 4. Final configurations of filaments surrounded by pillars of radius $R = 6$ at a distance $D = 15$ placed along the long axis at (a) $x = 25$, (b) $x = 30$, (c) $x = 35$, (d) $x = 40$, (e) $x = 45$, (f) $x = 50$, (g) $x = 55$, (h) $x = 60$, and (i) $x = 65$.

Figure 4 shows the effect of moving the pillars to different x -positions along the long axis of the filament. Perhaps the most interesting feature is highlighted by figures 4(a–d), where we observe competition between two different instability types: filament break-up, as considered in the context of figure 2, and edge instability. The latter case has been studied for finite-length filaments; see e.g. work on liquid PDMS filaments (González *et al.* (2007) for experimental results, and Diez *et al.* (2009) for a theoretical and computational discussion). In a broader context, relevant mathematical discussions on the influence of finite-length effects can be found in work by van Saarloos (2003), while experimental results in set-ups focusing on related but different physical effects (such as a stretched drop in a four-roll mill geometry) were presented by Stone & Leal (1989). A critical aspect of the current problem is localised heating, which leads to asymmetric break-up as illustrated in figure 4(a), where the drops form only on one side of the filament. In this particular case (figure 4(a)), the drop formation mechanism is different to the RP mechanism of figure 2(b): here, it is due to retraction of a filament edge that first forms a ‘bulge’, which then breaks off from the rest of the filament; supplementary movie 2 illustrates this process in more detail. We note that for the present geometry, the drops that form due to such an edge instability and those that typically form due to RP break-up of a filament are of the same size, which we refer to as V_{max} in what follows. This V_{max}

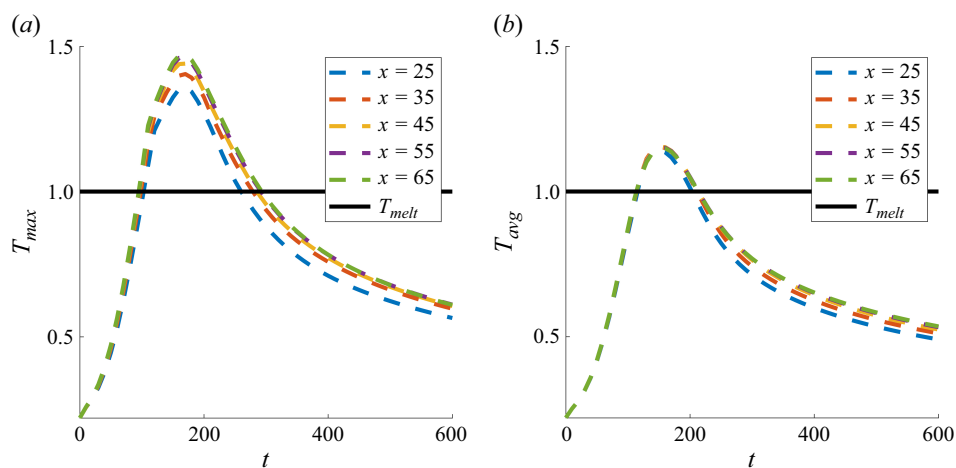


Figure 5. (a) Maximum temperatures and (b) average filament temperatures for the results in figure 4.

is determined approximately by the wavelength of maximum growth emerging from the linear stability analysis of an infinite filament, and mass conservation; see Diez *et al.* (2009) for more details.

Figures 5(a) and 5(b) show the maximum and average temperatures, respectively, of selected filaments in figure 4. From figure 5(a), we see that the maximum filament temperatures increase as pillar distance from the centreline of the filament ($x = 70$) decreases. When the pillars are located near the edge of the filament (e.g. $x = 25$), heating is more localised, leading to lower peak temperatures, whereas when the pillars are closer to the centreline (e.g. $x = 65$), temperatures are higher because of the more symmetrical heating. Supplementary movie 2 shows the evolution in the cases $x = 25$ and $x = 35$. Interestingly, the symmetry of the heating with respect to the pillars' location dictates the location of maximum temperature. In the $x = 35$ case, the heating is sufficiently symmetric that the maximum occurs at $x = 35$, whereas in the $x = 25$ case, the maximum temperature occurs within the retracting droplet, displaced from the location of the pillars.

Figure 5(b) shows the corresponding average filament temperatures. In the early stages of heating, the temperature profiles are nearly identical; even though the pillars are placed at different positions, the total volumetric absorption of the filament is essentially the same, leading to similar average filament temperature across the cases. After the peak, and consistent with figure 5(a), temperatures are lowest in the $x = 25$ case (pillars furthest from the filament centreline), reflecting differences in filament evolution.

Progressing along the consecutive snapshots in figure 4 provides further insight into the details of the instability evolution. In figure 4(a), the edge drop forms at approximately $x = 31.5$, while the initial filament edge is at $x = 20$; this considerable retraction is due to strong heating and associated decrease of the relevant time scale (due to temperature-dependent viscosity), leading to significant surface-tension-driven motion. In contrast, the edge droplets are formed at $x = 30.3, 29.5, 28.3$ for figures 4(b,c,d), respectively. In these cases, edge retraction occurs before major undulation growth in the bulk filament, essentially completing its movement before approximately $t = 170$ (near the peak temperature time); in contrast, the filament solidifies entirely at approximately $t = 300$. The slight decrease in edge droplet transport going from figure 4(a) to figure 4(d) is primarily due to the increasing distance between the pillars and the left-hand end of the filament, which diminishes the heating there, increasing the viscosity. As the pillars are

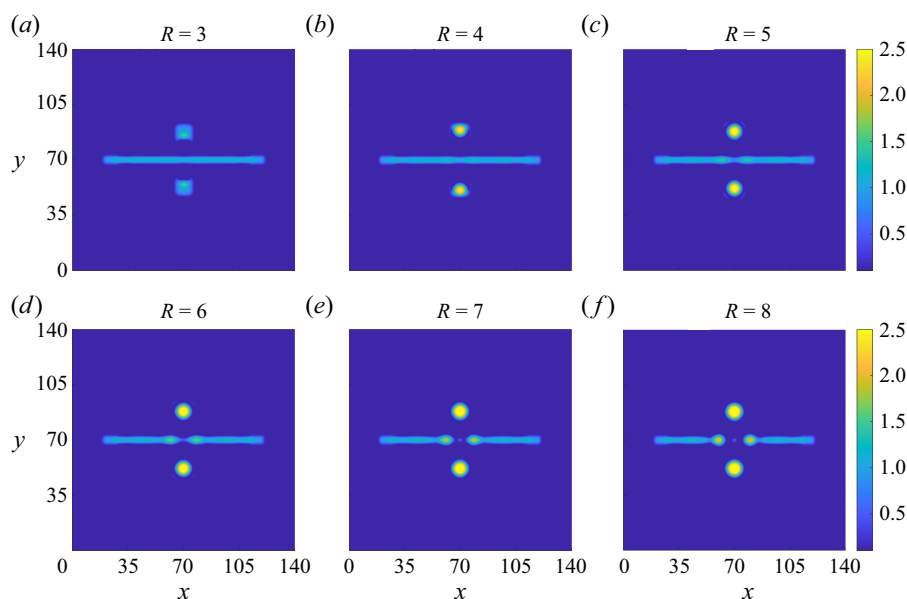


Figure 6. Final configuration of filaments surrounded by pillars of radii $R = 3$ to $R = 8$, with distance between pillar centre and filament long axis set to $D = 15$. In (a–c), the heating from the small pillars leads to minor undulations without break-up, whereas the increased pillar size in (d–f) leads to break-up of the filament commensurate with the position of the pillars. Plot (d) is the same as in figure 2(b).

moved towards the vertical line of symmetry, end effects are lost, and the filament breaks at the intersection of the line connecting the pillars' centres and the filament's long axis – an effect that we term ‘thermal scissors’.

Figure 6 shows that the pillar-assisted-break-up of the filament depends on the size of the pillars. When the pillars are sufficiently small as in figures 6(a–c), the filament experiences at most small undulations prior to re-solidification. As the pillars increase in size and absorb more heat (that is transmitted to the filament via the substrate), these instabilities become strong enough to break the filament. Moreover, in figures 6(e,f), the break-up results in the formation of an additional small satellite droplet at the domain centre, a feature that we will revisit below. We also note that the thermal interaction between filament and pillars goes in both directions; this is perhaps most obvious in figure 6(a), where we see that only one part of the pillars (that closest to the filament) melts. Supplementary movie 3 shows the metal evolution and temperature for figures 6(c,e), displaying how even small differences in temperature can lead to significantly more dewetting.

Focusing now on the satellite drop formation that was noted in figures 6(e,f), figure 7 shows the influence of the pillar distance D from the filament. A small distance leads to filament break-up, symmetric with respect to the pillars, with a large central drop, comparable in volume to V_{max} (figure 7(a), $D = 10$). The size of this drop decreases as the pillars are moved away from the filament (figure 7(b), $D = 10.5$), shrinking abruptly to just a small ‘satellite’ droplet as D is increased further (figures 7(c,d), $D = 10.75, 11$). Supplementary movie 4 shows the dynamics of the break-up process, and figure 8 shows the corresponding maximum and average filament temperatures. We view the simulations of figures 6(e,f) and 7 as special cases of the ‘thermal scissors’ effect, which we distinguish by the terms ‘thermal scissors with satellite droplet’ and ‘thermal scissors with central droplet’.

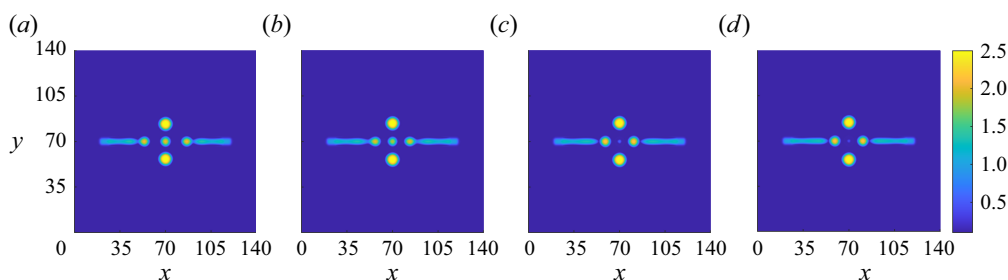


Figure 7. Final configuration of filaments surrounded by two symmetrically-placed pillars of radius $R = 6$ at distances (a) $D = 10$, (b) $D = 10.5$, (c) $D = 10.75$, (d) $D = 11$.

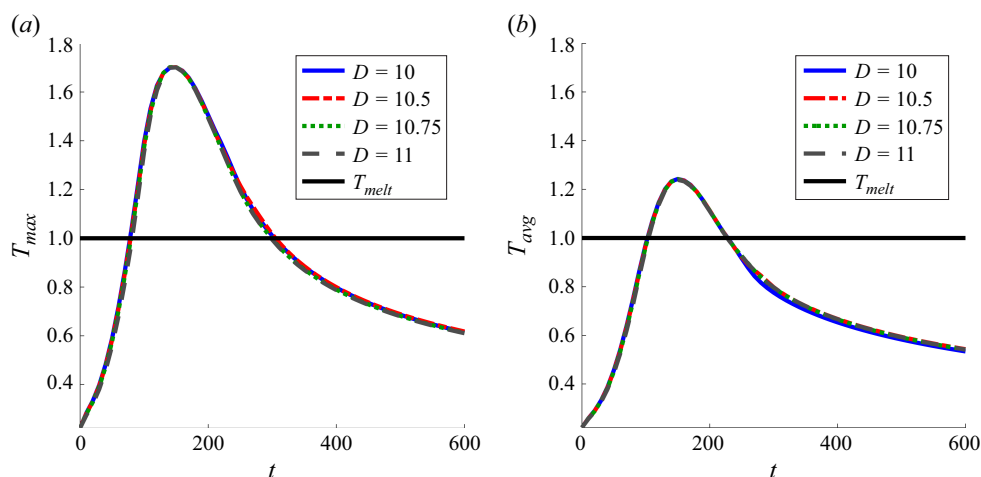


Figure 8. (a) Maximum temperature and (b) average temperature of the filaments from figure 7, namely $D = 10$ (blue solid line), $D = 10.5$ (red dashed line), $D = 10.75$ (green dotted line), and $D = 11$ (grey dashed line). The melting temperature is given by the solid black line.

We note that $D = 10$ represents the smallest separation for which the filament and pillars remain distinct throughout the evolution; for smaller values of D (results not shown), mass transfer between the filament and pillars may occur, which lies outside the scope of the current model. Supplementary figure 1 shows that no mass transfer occurs for $D = 10$.

The temperatures for $D = 10, 10.5, 10.75, 11$ are nearly identical, yet the fluid dynamical outcomes are qualitatively different. This is further illustrated by figure 9, which shows longitudinal filament cross-sectional profiles and cross-sectional temperatures for the simulations of figures 7(a,b,d): despite the clear differences in the filament geometries in figures 9(a,c,e), figures 9(b,d,f) consistently demonstrate very similar temperature profiles across the various D values. Our interpretation of these results is that the break-up process depends strongly on the length of the filament's melted portion and its temperature. Small differences, due to slightly modified pillar positions, can lead to large differences in the final outcome, as they may change the number of unstable undulations on the filament surface (supplementary movie 4 clearly shows this effect). Although the break-up process is extremely sensitive to the pillars' positioning, it is also highly predictable, with a clear trend in outcomes as the distance between the pillars and the filament varies. This is highlighted in figure 10, wherein figures 10(a-c) show zoomed-in images of the central droplets, once in their final re-solidified state,

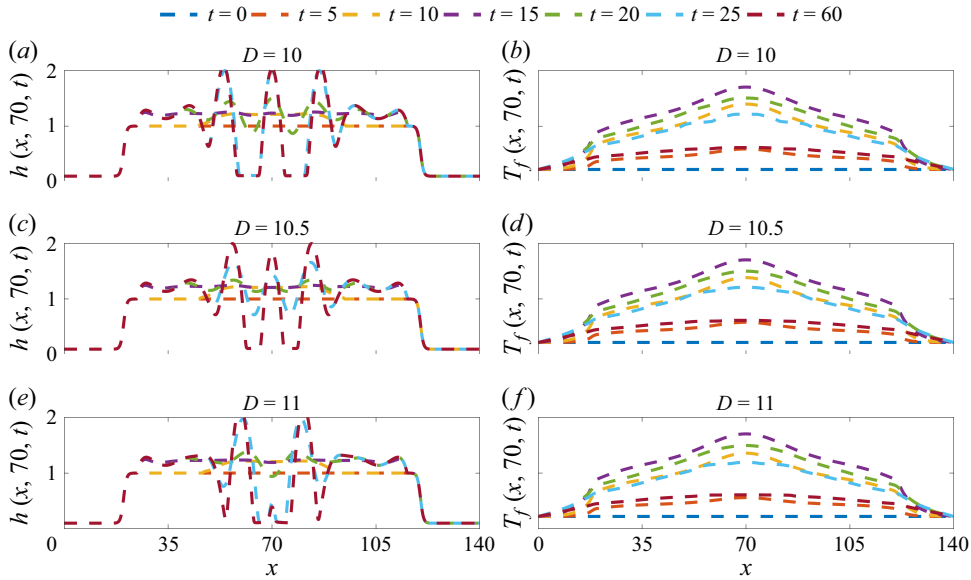


Figure 9. (a,c,e) Filament thickness and (b,d,f) temperature for longitudinal cross-sections ($y = 70$) of figures 7(a,b,d), where (a,b) $D = 10$ (figure 7a), (c,d) $D = 10.5$ (figure 7b), and (e,f) $D = 11$ (figure 7d).

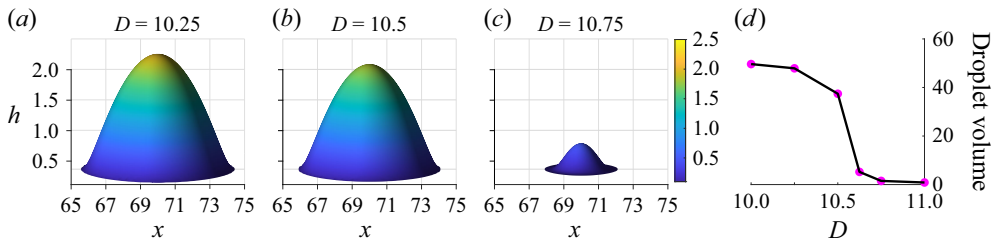


Figure 10. Central droplets formed when the two pillars are at distance (a) $D = 10.25$, (b) $D = 10.5$, (c) $D = 10.75$. The droplets shown here in (b,c) correspond to the central droplets in figures 7(b,c). Plot (d) shows the drop volume versus D , indicating a steep decline between $D = 10.5$ and $D = 10.625$.

for $D = 10.25, 10.5, 10.75$, respectively. Figure 10(d), which shows the central droplet volume for different D values, suggests that the break-up process can be formulated as a second-order phase transition (pitchfork bifurcation). The inner droplet size decreases sharply but continuously as the pillar distance increases, with an approximately 86 % decrease in droplet volume occurring between $D = 10.5$ and $D = 10.625$. Therefore, a bifurcation occurs between these values, where $D < 10.5$ leads to primary-sized droplets of approximate volume V_{max} , and $D > 10.625$ leads to satellite droplets.

4.2. Effect of multiple adjacent pillars on filament evolution

Next, we illustrate how multiple pillars influence the evolution. We focus on the simple geometry involving four pillars placed symmetrically with respect to the short and long filament axes of symmetry; the analogous case with two symmetrically placed pillars was considered in figure 2(b). Figure 11 shows the case of a filament surrounded by pillars at distance $D = 10$ (figures 11a–c), $D = 12.5$ (figures 11d–f) and $D = 15$ (figures 11g–i), with pillar–pillar separation $S = 20$ (figures 11a,d,g), $S = 24$ (figures 11b,e,h), and $S = 30$

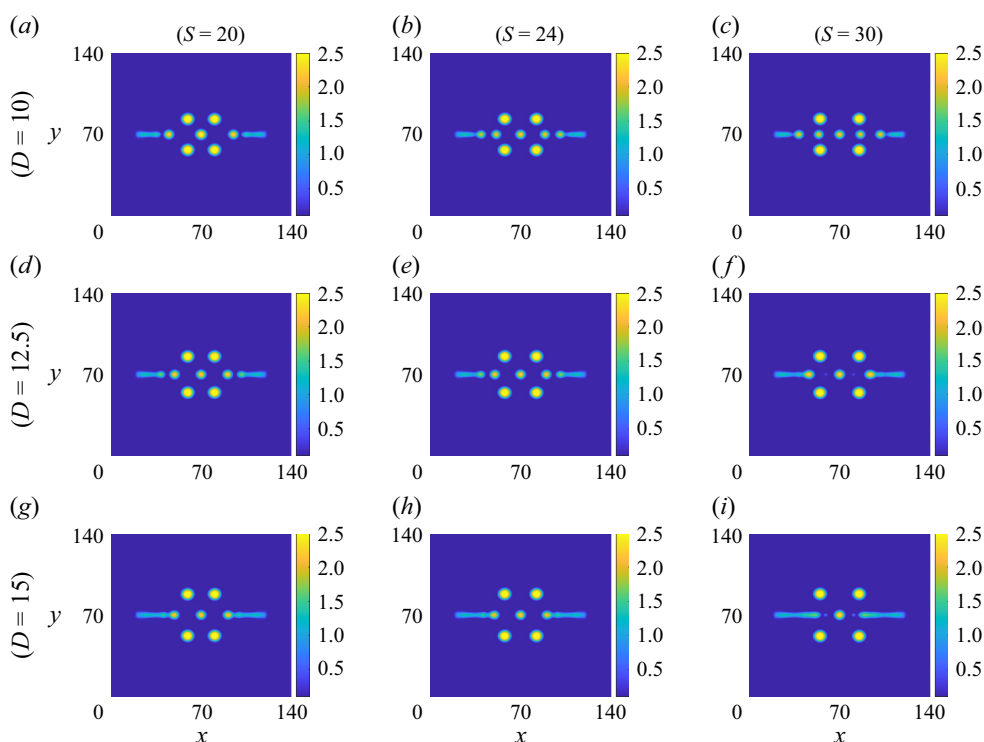


Figure 11. Final configuration of a single filament surrounded by four pillars at pillar–filament distances (a–c) $D = 10$, (d–f) $D = 12.5$, (g–i) $D = 15$, and at pillar–pillar separations (a,d,g) $S = 20$, (b,e,h) $S = 24$, (c,f,i) $S = 30$.

(figures 11c,f,i). The maximum temperatures (red) and average filament temperatures (blue) for figures 11(a,c) are given in figure 12(a), and the temperatures for figures 11(g,i) are given in figure 12(b). We observe, as expected, that four pillars lead to enhanced filament heating and consequently to filament break-up away from the central point. The result is once again the formation of a central droplet, whose size, shown in figure 12(c), depends on the positioning of the pillars along the x -axis, measured by their separation distance S .

For $D = 15$, and the values of S studied here, the size of the central droplet increases monotonically with S , as seen in figure 12(c). The idea is that as S increases, the filament break-up points (the thermal scissors effect) are farther apart, so the separated central part of the filament has a larger volume and eventually retracts into the central droplet. This suggests a much higher degree of control over the central droplet size by tuning S than by tuning D . Evolution is shown in supplementary movie 5. For sufficiently large values of S , neighbouring satellite droplets also appear. Similar behaviour is observed in the $D = 12.5$ case (figures 11d–f), except that additional heating, due to the decreased pillar–filament distance, accelerates the evolution and enhances the rupture of secondary droplets near the centre. Notably, the secondary droplets form fully in the $S = 20, 24$ cases, with unformed tertiary droplets part of the remaining filament segments at the edges.

The $D = 10$ case (figures 11a–c) shows a different behaviour from the rest: figure 12(c) reveals that increasing S actually decreases the central droplet size. When $S = 20$ (figure 11a), the additional heating provided by the sufficiently close pillars leads to a large central droplet and secondary droplets far from the centre. On the other hand, when $S = 24$

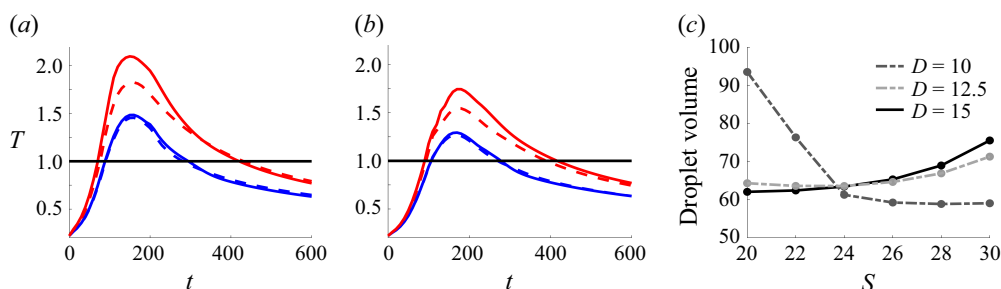


Figure 12. For (a) $D = 10$ and (b) $D = 15$, the average filament temperatures (the average over the material region, blue) and the maximum temperatures (red) for $S = 20$ (solid lines) and $S = 30$ (dashed lines). The solid lines in (a) correspond to figure 11(a), whereas the dashed lines in (a) correspond to figure 11(c). Solid and dashed lines in (b) analogously correspond to figures 11(g) and 11(i), respectively. In each of (a) and (b), the melting temperature is given by the solid black line. (c) The volume of the innermost droplet in figure 11 is shown as a function of S for $D = 10$ (black dashed line), $D = 12.5$ (grey dashed line), and $D = 15$ (solid black line).

(figure 11b), the pillars are sufficiently far apart to direct some inner filament material away from the central droplet to the remaining parts of the filament. The volume of the central droplet is further reduced in the $S = 30$ case, and the positions of the secondary droplets are now well aligned with the centreline of the pillars. In both the $S = 24$ and $S = 30$ cases, tertiary droplets are nearly formed.

5. Conclusions

This paper discusses the use of thermal effects to produce and control instabilities inherent to fluid filaments on substrates. While we focus on a rather specific system (metal filaments that remain solid unless heated) and simple geometry (filaments and pillars), our findings apply more generally to any fluid with temperature-dependent material parameters (viscosity in particular). For the simple geometry considered in this work, we illustrate both the extreme sensitivity of the outcome to geometric details and, at the same time, a high degree of control over the final outcome.

The majority of our study focuses on a metal filament surrounded by a pair of adjacent pillars, symmetrically positioned with respect to the filament's long axis. For this scenario, we find that the final outcome, after application of a single laser pulse, depends on both the location of the pillars relative to the filament's centreline/end, measured by the x -coordinate of the pillar centres' location, and the distance between the pillars and the filament in the perpendicular (y) direction. While the presented results illustrate the possible outcomes, it is instructive to see a more detailed breakdown of the interplay between these two parameters. To this end, we conducted a parameter sweep to construct the regime map shown in figure 13. Here, we analyse the filament break-up mechanisms for various values of pillar–filament distance D and pillar centre x . The data points along the $D = 15$ line correspond to the results of figure 4, whereas the final metal configurations of the remaining simulations are given in figures presented as part of the supplementary material. Each simulation may be classified according to one or more of the four distinct regimes already noted: (i) thermal scissors (green diamonds), where variation in temperature modulates classical RP break-up into directed break-up; (ii) thermal scissors with central droplet (red squares), where similar modulation produces a central droplet exceeding a volume threshold ($V > V_{max}/2$) aligned with the centreline of the pillars; (iii) thermal scissors with satellite droplet (purple triangles), where similar

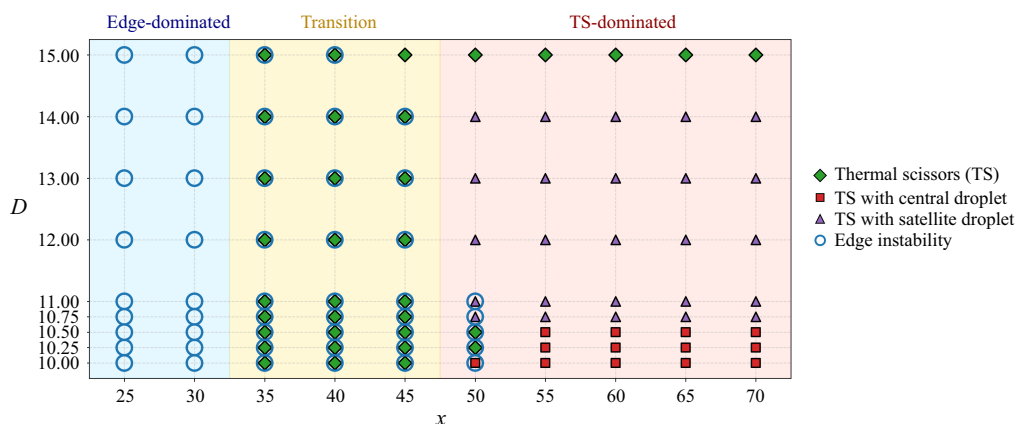


Figure 13. Regime map showing the break-up mechanisms of the filament with two adjacent pillars, for various values of pillar–filament distance D and location of pillar centre x ($x = 25$ being the end of the filament, and $x = 70$ the centre). Four distinct regimes are found: (i) thermal scissors (TS), where variation in temperature modulates classical RP break-up into directed break-up at the pillar location; (ii) TS with central droplet, where similar modulation produces a central droplet between the pillars, exceeding a volume threshold ($V > V_{max}/2$); (iii) TS with satellite droplet, where similar modulation leads to a droplet of sufficiently small volume ($V < V_{max}/2$); and (iv) edge instability, where curvature at the filament edge generates a Laplace-pressure-driven retraction, inducing an instability that simultaneously advects towards the filament centreline and grows towards rupture. Here, V_{max} is the drop size predicted by the linear stability analysis of an infinite-length filament.

modulation leads to a droplet of sufficiently small volume ($V < V_{max}/2$); and (iv) edge instability (blue circles), where curvature at the filament edge generates a Laplace-pressure-driven retraction that induces an instability that simultaneously advects towards the filament centreline and grows towards rupture. Here, V_{max} is the drop size predicted by the linear stability analysis of an infinite-length filament. The transition points as well as other features of the presented results show only minor changes upon further mesh refinement and temporal discretisation.

For small values of x (blue shaded region in figure 13), break-up is governed by edge retraction. In this regime, the filament edge retracts, inducing a neighbouring undulation that grows while the bulk material at the edge is transported inwards. This leads to the formation of a droplet (of volume $\approx V_{max}$) that originates at the filament edge. In some cases ($D \leq 12$), a secondary droplet forms that pinches even closer to the centreline. For intermediate values of x ($x = 35, 40, 45$), both edge retraction and targeted break-up via thermal scissors occur, on comparable time scales; the scissors promote instability growth (commensurate with the pillar centreline) by reducing viscosity, whereas the edge instability promotes an undulation near the filament edge that propagates towards the filament centreline. The combination of the two produces non-uniform break-up, resulting in irregular droplet spacing and multiple locations of filament rupture.

When the pillars are placed far enough from the edge ($x \geq 50$), the thermal scissors effect dominates over any edge retraction, inducing break-up commensurate with the pillars' centreline. While the edge instability is still present in some cases (e.g. $x = 50$, $D \leq 11$), its role is secondary and does not significantly alter the break-up. This finding is consistent with weaker heating of the filament edges when the pillars are far away. Therefore, the thermal-scissors-induced undulations have grown sufficiently that they play a dominant role in the break-up process. The final outcome is typically a filament that breaks up at an interior point, sometimes forming a central droplet.

Consistent with figure 7, the pillar–filament distance strongly controls the size of the central droplet that may form in the thermal scissors regime. In particular, there exists an intermediate range of values ($10.75 \leq D \leq 15$) over which satellite droplets are observed, separating regimes of large central droplet of volume $\approx V_{max}$ at low D , and no droplet formation at large D .

The richness of the set of outcomes that result from just the simple filament/two-pillar geometry, together with the intriguing findings of figure 11 for even a preliminary study of the filament/four-pillar geometry, demonstrate that it is possible to precisely control the size and position of the droplet pattern that results when a single filament breaks up. A systematic investigation of alternative pillar geometries, the construction of more elaborate phase diagrams analogous to that in figure 13 that characterise break-up mechanisms across an extended parameter space, and the consideration of alternative forcing (e.g. localised heating or varying laser pulse characteristics) remain interesting directions for future work.

Supplementary materials and movies. Supplementary materials and movies are available at <https://doi.org/10.1017/jfm.2026.11683>.

Declaration of interests. The authors report no conflict of interest.

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