

Coaxial Counter-Current Jet-Film Flows of Nanofluids and Metal Melts

IVAN KAZACHKOV

Department of Information Technology, Physical, Mathematical and Economic Sciences,
Nizhyn Mykola Gogol State University,
Grafka Street 2, 16600, Nizhyn, Chernihivska Oblast,
UKRAINE

Abstract: - This study presents a theoretical framework for coaxial nanofluid jets and film flows, as well as analogous flows of liquid metal melts. These systems are of considerable interest in heat transfer and other scientific and industrial applications. The modeling begins with the phenomenon of film formation resulting from hydraulic shock in coaxial counter-current jets. When two opposing jets collide, the abrupt deceleration of fluid velocity to nearly zero produces a thin, radially spreading film. This process is analogous to jet impingement on a solid plate, but conventional Navier–Stokes equations cannot adequately describe it, since they do not account for the sudden jet deceleration followed by film redistribution. Several nanofluids are considered, and the parameters of the resulting film flows are computed. These results provide valuable insights into film cooling and other applications involving liquid metals and nanofluid film flows.

Key-Words: - Nanofluids, Coaxial Jets, Counter-Current, Hydraulic Shock, Film Thickness, Flow Velocity.

Received: February 8, 2026. Revised: April 7, 2026. Accepted: June 21, 2026. Published: October 2, 2026.

1 Introduction

The phenomena of jet and film flows, as well as the development of thin films due to hydraulic shock on solid plates, have been extensively studied in prior works, for example, in analyses of parametrically controlled jet decay into droplets for industrial and technological applications such as metallurgy, tokamak systems, and the production of unique amorphous materials [1].

Film formation is a particularly intriguing process: a vertical jet striking a fixed horizontal plate (or disk) transforms into a thin horizontal film flow when the jet velocity is sufficiently high [1]. In the case of the hydraulic impact of a vertical jet on a horizontal disk, conservation laws of mass and momentum must be applied, with film thickness and flow velocity strongly influenced by the speed of sound in the liquid. A similar phenomenon occurs when two coaxial counter-current jets collide. In this work, we present mathematical modeling and computer simulations of these flows for nanofluids and liquid metals.

2 Creation of the Film Flows due to the Hydraulic Shock of the Jets

2.1 Film Flows in the Frame of the Navier-Stokes Equations

Considering film flow formation within the framework of the continuity hypothesis and the Navier–Stokes equations [2], [3] leads to a description of a smooth jet-to-film transition. However, this theoretical picture does not correspond to the experimentally observed process, as illustrated in Figure 1. In reality, the transformation involves an abrupt hydraulic shock: the jet velocity drops sharply to nearly zero at the impact point, followed by the sudden formation of a thin film.

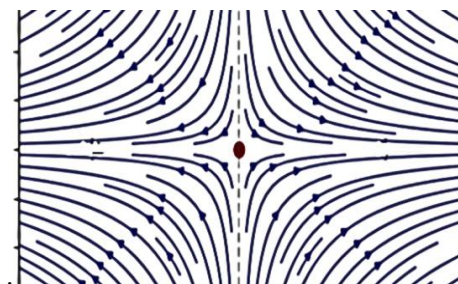


Fig. 1: Axis of the counter-current jet flows transforming to radial film flow

Source: created by the author

This discrepancy highlights the limitations of conventional continuum modeling. While the Navier–Stokes framework predicts gradual redistribution of flow, experiments show that film formation is inherently discontinuous, requiring additional modeling approaches to capture the dynamics of hydraulic impact and subsequent film spreading. The breaking point is in the center. The breaking point is in the center of the braking plane. This discrepancy arises because hydraulic shock is not captured by Navier–Stokes formulation. Thus, this is just a thin sheet flow.

Confined impinging jets (CIJs) are reactors used in processes that require fast mixing. In such equipment, two fluids are injected from opposite sides of a chamber, impinging on each other and forming flow structures that enable effective mixing and reaction. The turbulence analysis shows that the energy is injected from smaller scales, having approximately the injector's width, that feed larger-scale structures up to larger vortices that occupy the entire mixing chamber width.

This energy distribution has an inverse energy cascade, i.e., it is an inversion of the traditional description of homogeneous 3D turbulence. The typical flow scales of 2D CIJs are clearly shown to be linked to the 2D turbulence energy spectrum and to integral scales of turbulence. Moreover, the turbulence mechanisms in 3D CIJs at transitional flow regimes are shown to be similar to those in 2D CIJs.

The flow pattern when two opposing jets collide is characterized by the formation of a stagnation point or stagnation plane, where the flow velocity drops to zero, and the static pressure reaches a maximum. Basic elements of the flow pattern are:

- Impact zone: a region is formed in the center between the nozzles where the jets impinge on each other. If the jets are identical in power, this zone is located exactly in the middle.
- Radial spreading: After the collision, the liquid or gas deviates from the initial axis and spreads radially to the sides, forming a so-called "scattered" or "merged" jet.
- Vortex structures: Intense vortices arise at the boundaries of the jets and in the zone of their interaction. In turbulent regimes, this leads to rapid and efficient mixing of the components.

The flow pattern depends significantly on both the distance between the nozzles and the Reynolds number.

- At low Reynolds numbers and certain nozzle spacings, the pattern remains symmetrical and stable.
- As the jet velocity increases, the stagnation point begins to oscillate along the axis or perform "rolling" movements, which enhance turbulence.
- When the jets have unequal impulses (one jet more powerful than the other), the stagnation point shifts closer to the weaker source.

A study of the influence of viscosity on the characteristics of the thin "sheet" formed by the collision of two jets was presented in [3]. This work highlights how viscosity alters film thickness, stability, and the onset of instabilities in the sheet flow. The flow and temperature distributions for a column of materially buoyant fluid, referred to as a Cartesian compositional plume, rising in a less buoyant fluid contained between two parallel vertical planes were identified, and the material, heat, and buoyancy fluxes associated with them were discussed in [4]. The stability of the system to linear perturbations was investigated and found to depend on six dimensionless numbers.

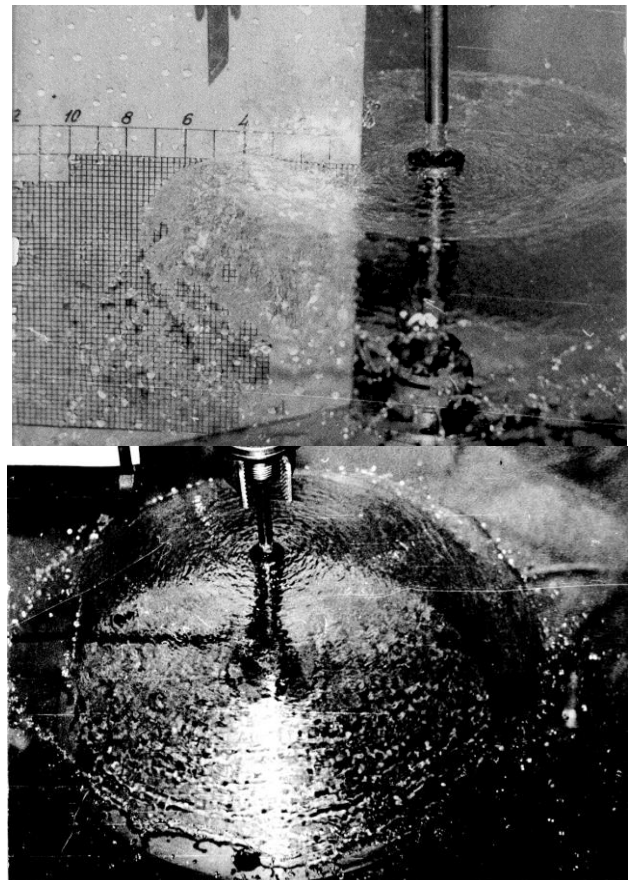


Fig. 2: Bending wave oscillations: vibrating disk
Source: [1]

But the situation shown in Figure 1 describes thin sheet flows and not real 2D thin film flows, which spread with supersonic velocities and reveal some elastic properties as a whole. The crucial difference between the thin sheet flow as in Figure 1 and real 2D thin film flows from our experiments in Figure 2 is in the condition of the hydraulic shock of the jet on a solid plate or on the meeting point of the two identical counter-current jets in Figure 3.

As seen from Figure 2, liquid film flow has some elastic properties. It reacts to the vibrating disk as a whole, similar to an elastic surface. Schematically, it is explained in Figure 3.

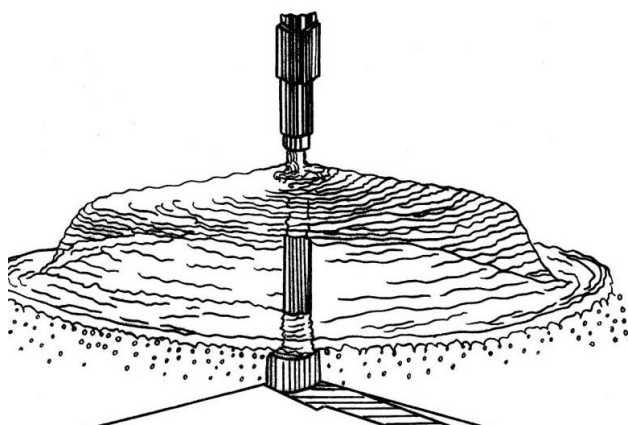


Fig. 3: Vibration control of bending oscillations
Source: [1]

When the jet nozzles are located close together, or when thin jets retain their shape due to capillary forces, the increased pressure at the center of collision, whether between opposing jets or between a jet and a solid surface, is directed strictly along the line of radial spreading of the thin film (diaphragm), as shown in Figure 2, Figure 3 and Figure 4.

A similar phenomenon can be observed in everyday life: when a jet of water from a kitchen tap strikes a spoon, the thin film spreads radially without any transitional smooth region, unlike the gradual jet-to-film transition illustrated in Figure 1.

2.2 Hydraulic Shock of the Jet with Plate

The unique two-dimensional thin film flows can be formed due to the shock of a jet with a solid plate and by the coaxial counter-current jets, as shown in Figure 3, Figure 4 and Figure 5.

The creation of a thin film flow is a distinctive phenomenon involving the transformation of a three-dimensional jet into a two-dimensional film. For example, when a vertical jet (or one inclined at an angle) impinges on a fixed horizontal disk at sufficiently high velocity, it spreads into a thin

horizontal film [1], [5], [6]. This phenomenon is often referred to as a veil or liquid sheet.

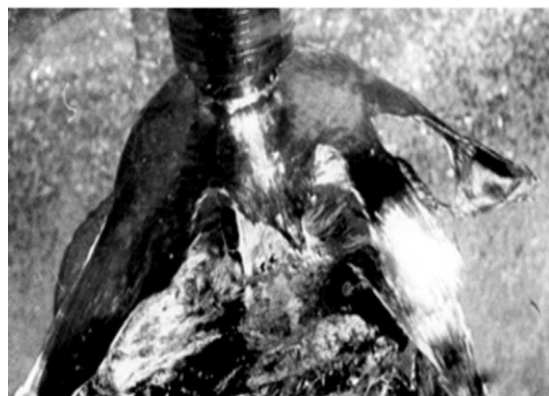


Fig. 4: Gallium film flow from impinging jet flow on a disk in a weakly controlled nitric atmosphere
Source: [1]

The crucial stage in this transformation is the abrupt deceleration of a portion of the jet fluid from high velocity to zero upon impact with the disk. This occurs over a short impact time (Δt), during which the decelerated mass initiates the formation of the two-dimensional thin-film flow:

$$m = \rho c \Delta t S, \quad (1)$$

Here, ρ denotes the liquid density, c the sound velocity in the fluid (corresponding to the propagation speed of small density perturbations), and S the jet cross-sectional area [1].

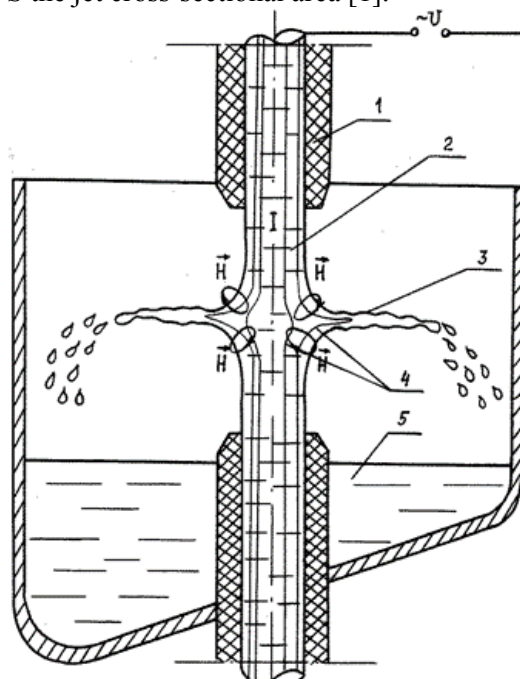


Fig. 5: Film flow from the hydraulic shock of coaxial counter-current jets: 1- nozzle, 2- vertical jet (symmetrical, the same from below), 3- film flow due to the shock of counter-current jets
Source: [1]

The product of this mass and the jet velocity defines the momentum of the decelerated portion of the jet, generated by its impact on the disk.

The first major distinction from conventional hydrodynamics lies in this phenomenon: a portion of the jet fluid is abruptly slowed from its initial velocity to zero at the speed of sound within a short impact time Δt . This abruptly decelerated jet mass determines the hydraulic shock exerted on the plate.

If the transformation of a jet into a film flow is considered without accounting for hydraulic shock, significant contradictions arise between theoretical predictions and experimental observations, particularly in terms of velocity and film thickness, except in the case of smooth, slow jets.

For the hydraulic impact of a vertical jet on a horizontal disk, it is essential to apply the conservation laws of mass and momentum. Despite the short impact time (Δt), the action exerted on the disk is much greater than that of a smooth flow, since the speed of sound in most liquids exceeds the jet velocity.

$$P \cdot S \cdot \Delta t = \rho \cdot c \cdot \Delta t \cdot S \cdot u_{00}, \quad P = \rho \cdot c \cdot u_{00}, \quad (2)$$

where $S = \pi r_0^2$ is the jet impact area, r_0 - radius of a jet, u_{00} - its velocity before impact with a disk.

As it is seen from (2), the action of the jet on the disk is much higher than that of a normal smooth flow, when it is equal to the kinetic energy of the jet $P = 0.5 \rho \cdot u_{00}^2$. For example, for a jet of water with a speed of 1 m/s, the pressure in the impact is about $1.5 \cdot 10^6$ N/m², which is 3000 times higher than the pressure of the same jet flow created on the plate (500 N/m²) without shock (smooth flow).

The limiting jet velocity required for film flow formation remains an open question and has not yet been investigated in detail. At a minimum, this velocity must exceed the frictional losses on the disk, though the precise threshold is unknown.

The radius of the resulting film flow depends on the jet momentum prior to impact, reduced by frictional losses along the disk surface and by viscous dissipation within the film. These factors determine how far the thin liquid sheet can spread radially before breaking down or losing coherence.

Similar phenomena occur in other contexts and must be analyzed in a comparable manner. For instance, storm waves striking a coastal barrage rise much higher than waves observed in open water. By analogy, the velocity of the film flow created after jet impact on a disk can be calculated using momentum conservation. The governing relation for the film flow is therefore expressed as:

$$\rho \cdot c \cdot u_{00} = 0.5 \rho \cdot u_0^2, \quad (3)$$

wherefrom, with account of the equation (3) yields

$$u_0 = \sqrt{2c \cdot u_{00}}, \quad a = 0.5 r_0 \sqrt{0.5 u_{00} / c}. \quad (4)$$

Thus, with an increase in the jet velocity, the film flow thickness grows.

Here, the mass conservation equation is used:

$$\rho 2\pi r_0 a u_0 = \rho \pi r_0^2 u_{00}, \quad (5)$$

a is the film thickness.

As seen from (3), the velocity of the film flow can be much higher than that of the impacting jet. In addition, the film thickness is much less than the jet's thickness by $u_{00} \ll c$. It was computed from (4) in the above conditions for the water jet of 1 mm radius, 1 m/s velocity, $c=1500$ m/s, as follows:

$u_0 \approx 54.8$ m/s, $a \approx 9.12 \cdot 10^{-3} r_0$, where from yields $a \approx 0.046$ mm for $r_0=5$ mm (jet creates film flow less than 0.1 mm thickness and a speed of 54.8 m/s!).

The viscous dissipation of flow energy was neglected in calculations. Therefore, these values are a little overestimated but still exciting. The ratio of various forces significantly depends on the film thickness, physical properties of liquid or metal melt, type, and intensity of the external influences that define a variety of flow modes.

An important role is played by the capillary, viscous, electromagnetic forces, etc. [1]. The radially spreading film flow has the same velocity as the plane one created by a plane jet [1], but its thickness is twice as less. Moreover, a film flow is spreading radially; therefore, its thickness ε is decreasing with the increase of the radial coordinate, which grows according to the mass conservation equation:

$$\rho 2\pi r_0 a u_0 = \rho 2\pi r \varepsilon u, \quad \varepsilon u = a u_0 r_0 / r, \quad (6)$$

where r is a radial coordinate (distance from the film circular flow origin), ε is the current film thickness at the distance r , and u is its velocity at a distance r from the origin. The momentum equation yields

$$\rho \pi r_0 a u_0^2 = \rho \pi r \varepsilon u^2, \quad \varepsilon = a u_0 r_0 / (r u), \quad (7)$$

where from follows that a film flow velocity is the same as previously got [1] for the plane film flow ($u=u_0$), while the thickness is varying starting from the origin $r=r_0$ following the correlation $\varepsilon=a r_0 / r$, thus, substantially, in contrast to the plane film flow. Due to this, the radial film flow is shorter than the plane film flow, as far as it moves with nearly constant velocity, permanently thinning.

Analysis of the mathematical model (3)-(7) shows that the limit value for the velocity of a jet is $u_{00} = c$. When the model remains valid, as far as afterward, the supersonic jet will create the shock wave itself (the shock-wave jet flow). The equation (4) results in the following parameters: $a = 0.35r_0$. For supersonic jet flow, there are conical shock waves on the head of a jet similar to the ones observed by us in the experimental study by high vibration acceleration (vibration Euler number $Eu_g = g_v r_0 / u_0^2$ was about 100 [1] shown in Figure 6, where $g_v = A\Omega^2$ - the acceleration due to vibration developed by the vibrator, A, Ω - the amplitude and frequency of the vibrations.

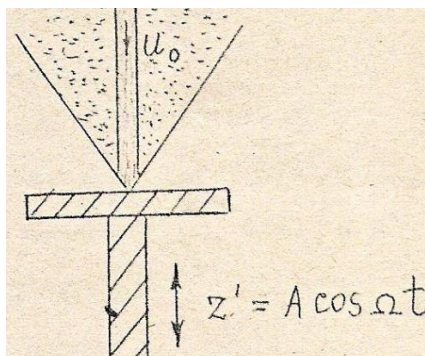


Fig. 6: The regime of shock-wave film flow as observed in experiments with water film flow Source: [1]

2.3 Creation of Film Flows due to Hydraulic Shock of Coaxial Counter-Current Jets

Taking into account all of the above and following the scheme illustrated in Figure 5, the film flow generated by the hydraulic shock of two coaxial counter-current jets can be derived in a similar manner.

In this case, the initial velocities of the jets are combined, along with their respective mass flows, at the point of impact. Consequently, instead of the single-jet velocity u_0 , the effective velocity for coaxial counter-current jets becomes $2u_0$. Therefore, according to equation (5), the resulting film flow thickness is determined by this doubled velocity and the associated mass flow conditions:

$$a = r_0 \sqrt{0.5u_{00} / c}, \quad (8)$$

twice as big as in (4). The others are the same.

2.4 Application of the New Phenomena of Controlled Film Flow

We can conclude that nanofluids have a weak increase in density but a substantial increase in the speed of sound and heat conductivity, as well as

heat transfer, can have a critical influence on both the flow and heat transfer characteristics of the film flows.

The speed of sound in molten metals is significantly higher than in liquids (kilometers per second) but lower than in the solid state due to reduced density. It depends on temperature but typically ranges from 3000 to 5000 m/s, significantly exceeding water (~1500 m/s).

Nanofluids (nanoparticles in a liquid) exhibit unique properties where the speed of sound can differ from the base liquid due to surface effects and nanoparticle interactions, often increasing with concentration, although the data are very specific to each type of nanofluid. For example, at room temperature (about 20°C), the speed of sound in water is about 1450 m/s; in molten metals (e.g., lead, tin), it can be in the range of 1200-2000 m/s, depending on the temperature of the melt and the specific metal.

With regard to the speed of sound in nanofluids, there are dispersions of nanoparticles (metal, oxide, carbon, etc.) in a base liquid. Moreover, the speed of sound depends on the properties of the nanoparticles (size, shape, material) and the carrier liquid. Nanoparticles increase the overall density of the nanofluid, which can increase the speed of sound.

Interaction at the nanoparticle-liquid interface and the elastic properties of the nanoparticles strongly affect sound. Heating can reduce the speed of sound, and the addition of nanoparticles often increases the speed of sound compared to a pure carrier fluid (e.g., water), e.g., nanofluids, water. For example, Nanofluids based on Al_2O_3 in water can have a sound speed 5-10% higher than pure water.

In the nanofluids based on carbon nanotubes, the speed of sound can be significantly increased depending on the concentration and orientation of the nanotubes. In general, nanofluids offer unique opportunities for controlling the speed of sound and heat transfer characteristics.

3 Calculation of the Parameters

3.1 Parameters of Liquid Metal Film Flows

According to (3) and (4), the speed of sound determines the thickness and velocity of the film flow formed because of the hydraulic shock of the vertical jet with the surface of the disk. Therefore, now we make estimates for the different liquids and melts, especially for the nanofluids.

The speed of sound is a constant of a given substance in gases, liquids, and isotropic solids. It is

determined by elasticity and density by the formula: $c = \sqrt{E/\rho}$, where E is the Young's modulus of elasticity. The speed of sound is minimal in gases (under normal conditions in the air, $c = 330$ - 340 m/s, depending on temperature T : the higher T , the higher the speed). Value c is maximal in solids ($c=6000$ m/s in steels), intermediate in liquids ($c=1500$ m/s in water). $M=u/c$ is the Mach number. Flow is supersonic when $M>1$.

The speed of sound is independent of frequency in an ideal gas but weakly depends on frequency in all real physical processes. This is a function of the square root of temperature, which does not depend on pressure and density in a given gas.

Let's take the following average values for the speed of sound in aluminum (Al), gallium (Ga), copper (Cu), tin (Sn), lead (Pb), zinc (Zn) [7], which were used in our experimental studies and in the production of granules [1]: 4700, 2800, 3460, 2400, 1800, 2800 (m/s). Then from the formulas, (3)-(5), the following approximate expressions for calculating the film velocity and its thickness are written as:

$$u_0 = \alpha \sqrt{u_{00}}, \quad a/r_0 = 0.5\gamma \sqrt{u_{00}}, \quad a/r_0 = \gamma \sqrt{u_{00}} \quad (9)$$

For the jet film flows and coaxial counter-current jet film flows, respectively. Here α, γ ($\gamma=1/\alpha$) The constants of the material are presented in Table 1.

It is evident that water and mercury are close to these indicators, while the other metal melts are very different, especially aluminum, which has a speed of sound almost twice as high as water: with the same parameters of the jet, the aluminum film will be twice as fast and thinner than the corresponding film of water. For a radial film, according to (5), the constant γ is twice less than that presented in Table 1.

Table 1. The values of the speed of sound and parameters α, γ for melts and water

Liquid	$c, m/s$	$\alpha, \sqrt{m/s}$	$\gamma, \sqrt{s/m}$
Aluminum	4700	97.0	0.010
Iron (Fe)	4200	91.7	0.011
Cu	3460	83.2	0.012
Ga, Zn	2800	74.8	0.013
Sn	2400	69.3	0.014
Pb	1800	60.0	0.017
Water	1500	54.8	0.018
Hg	1450	53.9	0.019

Source: created by the author

Velocity and thickness of the film flows created by the impact of the counter-current jets, depending

on the jets' velocity, are given in Table 2, where the values higher than the corresponding speed of sound are in bold.

Table 2. Velocity u_0 (m/s) and $(a/r_0) \cdot 10^3$ for counter-current jet-film flows depending on velocity

$u_{00}, m/s$	10^{-2}	0.1	1.0	10	10^2	10^3
Al	9.7 1.0	30.7 3.2	97 10	307 32	970 100	3070 320
Cu	8.32 1.2	26.3 3.8	83.2 12	263 38	832 120	2630 380
Ga, Zn	7.48 1.3	23.7 4.1	74.8 13	237 41	748 130	2370 410
Pb	6.0 1.7	19.0 5.4	60 17	190 54	600 170	1900 540
H ₂ O	5.48 1.8	17.3 5.7	54.8 18	173 57	548 180	1730 570

Source: created by the author

The corresponding thickness of the film flow created by the impact of the jet on a disk is twice less than the impact of the jet on a disk is half, with the same velocity.

The velocity of the film flow, determined by the velocity of the coaxial counter-current jets that form it, can be directly inferred from the preceding analysis. Importantly, in certain regimes, the resulting film flow velocity may exceed the speed of sound in the given medium, highlighting the critical role of acoustic properties in the dynamics of hydraulic shock and film formation.

Thus, for the melt of aluminum at $u_{00}=0.001$ m/s, the film velocity is $u_0=3.07$ m/s; then, at $u_{00}=1000$ m/s, respectively, $u_0=3070$ m/s, the impressive film velocity, and it's subsonic for the aluminum. In this case, $a/b=0.32$ and 320 respectively, which means that a film thickness of 1.6 microns ($a=1.6 \cdot 10^{-6}$ m) for a jet of 10 mm thick ($b=5$ mm) at $u_{00}=0.001$ m/s, and $a=1.6$ mm - at $u_{00}=1000$ m/s. In the latter case, this does not seem like a film, but a simple split of the flow according to the equations of smooth fluid flow, although a small compression of the jet on the disk is still observed.

It is evident that micron-scale film thicknesses can only be achieved when jets of approximately 1 mm radius are applied. For such jets, the corresponding film thickness values are:

- $\varepsilon=0.08 \mu m$ at $u_0=0.001$ m/s,
- $\varepsilon=0.25 \mu m$ at $u_0=0.01$ m/s,
- $\varepsilon=0.8 \mu m$ at $u_0=0.1$ m/s,
- $\varepsilon=2.5 \mu m$ at $u_0=1$ m/s.

In the latter case, according to equation (5), the film thickness at a distance of 2.5 jet radii is $\varepsilon=1\ \mu\text{m}$, while at 25 jet radii it decreases to $\varepsilon=0.1\ \mu\text{m}$. Such thin, high-pressure jets are employed in specialized applications, for example, in surgery as so-called “water scalpels,” where ultra-fine water jets replace conventional metal scalpels.

Nanofluids show measurable changes in the speed of sound compared to pure base fluids, depending on nanoparticle type, concentration, and temperature. For example, Al_2O_3 – water Nano fluids typically range around 1500–1600 m/s, while Ag–ethylene glycol nanofluids can exceed 1700 m/s, significantly higher than their base fluids:

1. Water-based nanofluids. In water, the speed of sound increases anomalously with temperature up to a peak (around 74°C), after which it begins to fall. The addition of nanoparticles shifts these values: Al_2O_3 (Aluminum Oxide) – Water: The speed of sound is approximately 1490–1580 m/s (depending on concentration and temperature, 298–343 °K).

As the particle concentration increases (up to 5 vol%), the speed generally increases. Ag (Silver) – Water: Experimental data show values in the range of 1495–1550 m/s at temperatures around $25\text{--}70^\circ\text{C}$. ZnO (Zinc Oxide) – Water: A slight decrease in the speed of sound is observed with increasing particle concentration due to increased particle interactions and increased density.

2. Ethylene Glycol-based Nanofluids. Basic ethylene glycol has a speed of sound of around 1650 m/s at room temperature. CuO (Copper Oxide) – Ethylene Glycol: The speed of sound varies smoothly in the range of 1600–1700 m/s. Increasing temperature leads to a weakening of intermolecular forces, which reduces the speed of sound. Al_2O_3 or Ag – Ethylene glycol: The speed of sound in these nanofluids is usually lower than in their aqueous counterparts and is 1580–1660 m/s.

3. Magnetic nanofluids (Fe_3O_4). The speed of sound in magnetic nanofluids (e.g., magnetite in oil or water) strongly depends on the external magnetic field: Without a field, the speed is about 1400–1500 m/s. In a magnetic field, the speed of sound increases significantly (up to tens of m/s) along the field lines due to the formation of chain structures from nanoparticles.

Main influencing factors:

- Concentration: In most systems (e.g., Al_2O_3 -water), the speed of sound increases with the volume fraction of particles.
- Temperature: Increasing the temperature usually reduces the speed of sound in organic bases, but

in aqueous systems it initially increases to a maximum.

- Particle size: Smaller particles provide better stability, which affects the uniformity of acoustic wave propagation.

3.2 Parameters of Ethylene Glycol (EG) – Nickel (Ni) Nano Film Flows

Different heat exchange fluids are used in heat management systems, and ethylene glycol (EG) is one of them, which is frequently used as a coolant due to its lower freezing point.

EG is considered better than water as well as other fluids due to its better heat transfer properties [8]. In this paper, the Ni-EG nanofluids were studied, and different physical parameters were measured for various concentrations at three different temperatures of 298.15 K, 303.15 K, and 308.15 K.

The experimentally measured values of density (ρ), speed of sound (U), and viscosity (η) were presented [8]. Density is a weak function of both the temperature in the above range and the concentration of the nanoparticles, with a total variation of less than 1%. Viscosity varies more strongly depending on temperature (e.g., approx. from 20.84 to 15.69 kNs/m²) than on the weight concentration of the nanoparticles in the range from 0 to 0.25%.

The speed of sound grows with nanoparticles concentration nearly linearly till 0.20% and then slightly falls by 0.25%, the same for all temperatures. With the temperature of nanofluid, the speed of sound is falling down a little more than growing depending on the concentration of nanoparticles. The speed of sound in nanofluid decreases slightly more than it increases, depending on the concentration of nanoparticles.

The influence of both temperature in the specified narrow range, as well as concentration of the nanoparticles on the film flow thickness and velocity is negligible. Thus, Ni-EG nanofluid film flow is nearly the same in terms of film thickness and velocity of the film flow. Nevertheless, the heat conductivity and heat transfer coefficients can substantially depend on the nanoparticle concentration.

3.3 Parameters of EG – Oxides Nano Films

The speed of sound in nanofluids, which represent different engineered colloidal suspensions of nanoparticles in the base liquids, highlights how even small volume fractions of nanoparticles significantly alter acoustic propagation. Moreover, it

generally increases with the nanoparticle concentration and decreases with rising temperature [9], [10], [11]. For example, Alumina (Al_2O_3) in water has the speed of sound in the range of about 1500- 1550 m/s; Copper (Cu) in water – 1510- 1530 m/s, depending on particle size and surfactant; Silver (Ag) in Ethylene Glycol- 1660- 1700 m/s (increases with Ag concentration).

Magnetic Fluids (MF) in the oil/water have about 1100-1450 m/s and can be tuned by the external magnetic fields. Remarkably, seawater in the temperature range from 0 to 30 °C shows great variation in sound speed, ranging from 1448 to 1546.

The particles of TiO_2 in distilled water show the change of sound speed in the concentration range of 0~40%: it decreases as the concentration increases until 30 wt.%, and then it increases after 30 wt.% [11]. Interesting to note that heat transfer characteristics are substantially enhanced by nanoparticles [9], as shown in Table 3.

Table 3. Properties of oxides and their nanofluids

Particles	Thermal conduct tivity W/mK	Density g/cm ³	Viscosity (cP) with 5.0 vol.% 30°C	Therm conduct enhanc. of nanofluids 5.0 vol.%
MgO	48.4	2.9	17.4	40.6
TiO_2	8.4	4.1	31.2	27.2
ZnO	13.0	5.6	129.2	26.8
Al_2O_3	36.0	3.6	28.2	28.2
SiO_2	10.4	2.6	31.5	25.3

Source: created by the author

Table 3 shows very different interesting features of different nanofluids based on oxides. The thermal conductivity of the nanofluid with MgO particles is the highest. Close to it is only the nanofluid with Al_2O_3 particles, whose density is slightly bigger but viscosity is substantially higher. A nanofluid with ZnO has dramatically high viscosity; therefore, its film flow is much shorter than the other ones.

The higher viscosity of zinc oxide (ZnO)-based nanofluids compared to other types under the same conditions is due to the specific physicochemical properties of the particles and their interaction with the base fluid. Tendency to aggregation has the following impact: ZnO nanoparticles have high surface energy and a specific isoelectric point (around pH 9.5). In neutral media (such as water), the surface charge is often insufficient to overcome Van der Waals forces, leading to the rapid formation of large clusters and aggregates. These structures increase the "effective" volume fraction of the solid

phase, which significantly increases the flow resistance.

Particle morphology also influences a lot: ZnO often forms non-spherical structures - Nano rods, "flowers," or rectangular shapes. Such particles have a larger aspect ratio (length-to-width ratio) than spherical ones, which creates greater hydrodynamic resistance when moving in a liquid.

Moreover, we have underlined the strong interfacial interaction: due to the high polarity of the ZnO surface, a dense adsorption layer of base liquid molecules (the so-called "Nano layer") forms around the particles. This actually increases the radius of the particle, making it "bulkier" for flow, which leads to an increase in the viscosity of the suspension.

Finally, the effect of ionic strength and pH: Zinc oxide is very sensitive to the chemical composition of the medium. The presence of even a small amount of salts (electrolytes) can cause "ionic bridging", where ions (e.g., Ca^{2+}) connect the particles together, further enhancing the structuring of the liquid and its viscosity.

3.4 Using the Oxides Nano Films

Obviously, the jet impingement of the nanofluid with thin film flow can be considered as a method for increasing cooling, application of uniform thin films on hard surfaces, Cold Thermal Energy Storage, Geothermal Heat Recovery, and in many other applications. The sound speed is so-called effective, which is significantly lower than that of pure DMF, even though the SWCNT bundles have a much higher sound speed than the DMF [12].

It was estimated that the change in sound speed was due to local heating of the DMF. For the nanofluid gold-water, it is reported [13] that the speed of sound at 10% vol. % 10% 900 m/s and at 15% - about 700 m/s.

Nearly all nanofluids create very close film flow parameters, both by thickness and velocity, because the different speeds of sound for them influence a little being under the square root in the correlations (3). Only the nanofluids TiO_2 -water and Magnetic Fluids in the oil/water remarkably differ.

Interesting to note also that seawater in the temperature range from 0 to 30 °C has a great difference in the speed of sound from 1448 to 1546. This means that film thickness and velocity of the film flow differ by about 3.3% when temperature changes from 0 to 30 °C, which is comparably small, but the other parameters (viscosity, heat conductivity, and heat transfer) change more strongly, so that application of the nanofluids is very

attractive in many cases [8], [9], [10], [11], [14], [15].

Magnetic Fluids allow controlling the film flow parameters, as well as the other parameters, making them attractive for a number of specific applications.

The parameter α in the formula (3), coefficient for the film flow velocity, varies for all fluids in the range 52-58, while for the liquid metals, it can be up to 97 (Table 1, Al melt). The film flows are supersonic due to their thin layer (two-dimensional flow!) and elastic properties, as seen from a number of experimental studies, e.g., shown in Figure 2 and Figure 3 [1].

Such high-speed thin-film flows are unique for many applications. This is different from the turbulent regime for the impingement of the thick jets by comparably low velocities when the flow after a solid plate is smooth and described by the Navier-Stokes equations [16], [17].

Nano fluid is a fluid containing suspended nanometer-sized particles, known as "nanoparticles", with a size of 1 to 100 nm, dispersed in a base fluid, are presently very well known in diverse applications like intensive heat transfer and others. It is very important to ensure that the size of the nanoparticles is less than 100 nm to achieve greater stability of the working fluid.

Typically, 5 types of nanoparticles are used to produce nanofluids, namely:

- metals such as gold (Au), silver (Ag), nickel (Ni) and copper (Cu);
- metal carbides such as silicon carbide (SiC);
- metal oxides such as zirconium oxide (ZrO₂), iron (II) oxide (Fe₃O₄), iron (III) oxide (Fe₂O₃), aluminum oxide (Al₂O₃), silicon dioxide (SiO₂), copper oxide (CuO), zinc oxide (ZnO) and dioxide;
- carbon materials such as carbon nanotubes, graphene and diamond;
- or metal nitrides such as aluminum nitride (AlN) and boron nitride (BN) [14], [15].

4 Discussion and Conclusions

Analysis of film flow formation is presented for two fundamental cases:

1. Hydraulic shock from jet impingement on a solid disk, where a vertical jet abruptly decelerates upon impact and transforms into a thin radial film.
2. Impact of coaxial counter-current identical jets, where two jets of equal velocity and radius collide head-on, producing a film flow through

the combined momentum and mass flux.

In both scenarios, the governing mechanism is the conservation of mass and momentum under conditions of hydraulic shock. The first case highlights the transformation of a three-dimensional jet into a two-dimensional film due to abrupt deceleration, while the second demonstrates how the effective velocity doubles ($2u_0$) when identical counter-current jets meet, leading to a distinct film thickness distribution as described in Figure 4.

Different metal melts and nanofluids were analyzed. In most studies, the spreading of films at relatively high velocities, whether across solid surfaces or in free space, is examined starting from the presence of the film flow itself, without addressing its formation as the result of hydraulic shock from a vertical or inclined jet striking a horizontal or inclined solid surface. Yet even a simple kitchen experiment, such as placing a spoon under a running water jet, reveals the striking phenomenon: a high-speed film flow that appears as a two-dimensional thin layer with elastic free-surface properties, sensitive to disturbances.

Several problems of heat and mass transfer in jet and film flows were considered, demonstrating that the creation of such film flows cannot be explained within the framework of conventional Navier-Stokes equations. Instead, their formation requires accounting for hydraulic shock and the abrupt transformation of jet momentum into thin film dynamics.

The thin film flow is generated by the hydraulic shock of a jet impinging on a solid plate. The parameters obtained in this case differ substantially from those predicted by classical hydrodynamic theory, because the shock decelerates a portion of the liquid from the impinging jet at the speed of sound. Consequently, the speed of sound becomes the governing factor in determining both the thickness of the resulting film and its spreading velocity. This highlights the fundamental distinction between conventional smooth jet-to-film transitions and shock-induced film formation, where acoustic properties of the medium play a decisive role.

The parameters of jet and film flows were obtained and computed for several metal melts and a range of nanofluids. It was shown that, despite the diverse physical properties of different nanofluids, the resulting film thickness and velocity are nearly identical. These similarities in flow behavior contrast with the differences in thermal conductivity and heat transfer characteristics, which remain strongly dependent on the specific fluid composition.

The radial film flow exhibits an almost constant velocity while its thickness decreases with distance from the impact point. This thinning explains the eventual disintegration of the film at larger radii. A unique feature of such flows is the supersonic regime, in which the film velocity exceeds the speed of sound in the medium. In this case, the film reacts to perturbations as a coherent whole, revealing elastic-like properties of its free surface.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

References:

- [1] Kazachkov I., *Boundary parametric control of oscillations in heat and fluid flows*, Cambridge Scholars Publishing, London, 2024. ISBN: 9781036451233 (print), 9781036410476 (ebook). DOI: 10.65325/EB11673.
- [2] Gonçalves D.N., Salvador H.M., Fonte C.P., Dias M.M., Lopes J.C.B., Santos R.J., On the 2D nature of flow dynamics in opposed jets mixers, *AIChE J.*, vol. 63, no. 6, pp. 2290–2302, Nov. 2016. DOI: 10.1002/aic.15291.
- [3] Yang L., Zhao F., Fu Q., Cui K., Liquid Sheet Formed by Impingement of Two Viscous Jets. *Journal of Propulsion and Power*, 30(4), 2014, pp. 1016–1026. DOI: 10.2514/1.B35105.
- [4] Al-Mashrafi K.S.M., The Linear Stability of Cartesian Plumes in a Bounded Region. *WSEAS Transactions on Fluid Mechanics*, 9, 2014, pp. 217–233. ISSN: 1790-5087. Conference location: Athens, Greece.
- [5] Li R., Ashgriz N., Characteristics of liquid sheets formed by two impinging jets. *Physics of Fluids*, 18 (8), August 2006, pp. 1–15. DOI: 10.1063/1.2338306.
- [6] Taylor G.I., Formation of thin flat sheets of water, *Proc. R. Soc. London, Ser. A* 259 (1296), 1960, pp. 1–17. DOI: 10.1098/rspa.1960.0207.
- [7] White M.A., *Physical Properties of Materials*. 3rd Edition. CRC Press, Boca Raton, FL, 2019. ISBN: 9781138605107 (print), 9780429887109 (ebook). DOI: 10.1201/9780429468261.
- [8] Gupta V., Sharma S., Sharma A.K. and Sharma M., Acoustical studies of nickel nanoparticles based nanofluids: Concentration and temperature dependent approach, *J. Indian Chem. Soc.*, Vol. 97, June, 2020, pp. 895-902.
- [9] Xie H., Yu W. and Chen W., MgO nanofluids: higher thermal conductivity and lower viscosity among ethylene glycol-based nanofluids containing oxide nanoparticles, *Journal of Experimental Nanoscience*, Vol. 5, No. 5, 2010, Oct., pp. 463–472. DOI: 10.1080/17458081003628949.
- [10] Majstorović D.M., Quindel P., Živković E.M., Kabelac S., A new setup for speed of sound measurements and experimental data for nanofluids Al₂O₃ or Ag with water or ethylene glycol, *Journal of Molecular Liquids*, Vol. 389, 1, November 2023, Article 122930. DOI: 10.1016/j.molliq.2023.122930.
- [11] Kim J., Chu M., Analysis of the Dependence of the Sound Speed in a Nano-Particle Suspension on the Concentration of Nano-Particles, *New Physics: Sae Mulli*, Vol. 67, No. 2, February 2017, pp. 243-247. DOI: 10.3938/NPSM.67.243.
- [12] Zhou W., Tiwari R.P., Annamalai R., Sooryakumar R., Subramaniam V., and Stroud D., Sound propagation in light-modulated carbon nanosponge suspensions, *Physical Review B* 79 (10), 2009, 104204. DOI: 10.1103/PhysRevB.79.104204.
- [13] Puliti G., Paolucci S., Sen M., Thermodynamic properties of gold–water nanofluids using molecular dynamics, *J. Nanopart Res*, vol. 14 (12), 2012, pp. 1-14. DOI: 10.1007/s11051-012-1296-4.
- [14] Rehman M.M., Qu Z.G., Fu R.P., Xu H.T., Numerical study on free-surface jet impingement cooling with nanoencapsulated phase-change material slurry and nanofluid, *Int. J. Heat Mass Transfer*, 109, 2017, pp. 312–325. <https://doi.org/10.1016/j.ijheatmasstransfer.2017.01.094>.
- [15] Feng X., Cousineau E., Bennion K.; Moreno G., Kekelia B., Narumanchi S., Experimental and numerical study of heat transfer characteristics of single-phase free-surface fan jet impingement with automatic transmission fluid, *Int. J. Heat Mass Transfer*, 166, 2021, 120731. DOI: 10.1016/j.ijheatmasstransfer.2020.120731.
- [16] Ooi J.W., Gunnasegaran P. and Hasini H., Effect of Hybrid Nanofluids Concentration and Swirling Flow on Jet Impingement Cooling, *Nanomaterials*, 12 (19), 2022, 3258. DOI: 10.3390/nano12193258.

- [17] Molana M. and Banooni S., Investigation of Heat Transfer Processes Involved Liquid Impingement Jets: A Review, *Brazilian Journal of Chemical Engineering*, Vol. 30, No. 03, 2013, pp. 413-435. DOI: 10.1590/S0104-66322013000300001.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The author has no conflicts of interest to declare that are relevant to the content of this article.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0

https://creativecommons.org/licenses/by/4.0/deed.en_US