

Vertical directional solidification (VDS) as an independent capillary-dominated solidification regime: Experimental evidence and physics of entirely detached growth under terrestrial gravity

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ABSTRACT:

Vertical directional solidification (VDS) enables a distinct crystal growth mode under terrestrial gravity in which the growing crystal remains entirely detached from the container wall through the formation of a continuous annular gap. In this work, experimental results are presented that establish detached growth in VDS as a robust and reproducible solidification regime rather than a marginal or transient condition. Detached growth is sustained over a wide range of axial thermal gradients without collapse of the free meniscus or degradation of the crystal–melt interface.

The observed stability cannot be explained by classical solidification theories developed for attached-growth systems, which implicitly assume wall-supported interfaces and gravity- or buoyancy-dominated normal force balance. Instead, the experimental evidence demonstrates a separation of normal and tangential physics in VDS: capillary pressure governs the normal force balance and stabilizes the interface, while thermocapillary effects act tangentially to redistribute heat and mass within the melt without inducing mechanical destabilization. This behavior is formalized through the Gadkari Detached Stability Criterion, which identifies capillary dominance as the governing condition for interface stability and explains the absence of a critical thermal gradient for collapse. These findings establish VDS as an independent, capillary-dominated solidification regime distinct from conventional directional solidification, floating-zone growth, and microgravity-assisted approaches. The results provide new physical insight into gravity-resistant crystal growth and define a framework for capillary-controlled solidification under terrestrial conditions.

Keywords: Vertical directional solidification; Entirely detached growth; Capillary-dominated solidification; Thermocapillary flow; Meniscus stability; Crystal–melt interface; Gravity-resistant growth; Microgravity materials processing

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I. INTRODUCTION

Directional solidification is a widely used method for controlled crystal growth, and its fundamental physics has been studied extensively over several decades. Classical descriptions of directional solidification focus on interface stability, melt transport, and microstructural evolution under the combined influence of gravity, buoyancy-driven convection, and thermal gradients (Wilcox et.al 2004). Within this framework, the crystal–melt interface is generally assumed to be mechanically supported by the container wall, and the normal force balance is treated as gravity dominated, with capillarity entering only as a secondary correction (Duffer 2010).

The stability of free surfaces and solidification fronts in such systems has been analyzed through gravity-controlled hydrostatic pressure and buoyancy-induced flow fields, with

particular attention to the role of surface tension in suppressing or modifying interfacial instabilities (Dreby et.al, 2004). At the contact line between the melt, solid, and container, capillary effects introduce additional length scales that influence interface shape and stability, although these effects remain constrained by wall attachment (Snoeijer et.al.2013). Classical solidification models therefore remain inherently tied to attached-growth configurations, where the presence of the container wall directly couples gravity, capillarity, and interface curvature (Kurz et.al.2006).

Thermocapillary (Marangoni) convection has been identified as an important transport mechanism in crystal growth melts subjected to temperature gradients (Shevtsova et.al 2006). The stability of thermocapillary flows with free surfaces has been studied extensively, revealing a wide

range of flow instabilities that can destabilize the solidification front under sufficiently strong thermal driving (Nepomnyashchy et.al 2007). perturbations and damping interface fluctuations under certain conditions (Simanovskii et.al.2013). More recent studies have examined the interaction between thermocapillary transport and directional solidification, emphasizing the sensitivity of interface morphology to thermal gradients and melt flow structure (Lan et.al. 2018; Chen et.al. 2012).

Directional solidification experiments conducted under reduced gravity have further clarified the role of buoyancy-driven convection in interface stability (Bergeon et.al.2005). Investigations of interface curvature effects confirmed that gravitational forces and wall constraints play a central role in determining solidification behavior in conventional systems (Liu et.al.2010). Capillary effects in melt growth have been explored in this context, primarily as modifiers of interface shape rather than as dominant stabilizing forces (Cröll et.al. 2016). Even under weak gravity conditions, interface stability analyses continue to rely on assumptions inherited from attached-growth models (Zhang et.al. 2021; Ma et.al. 2022).

Microgravity solidification experiments have provided valuable insight into free-surface dynamics and transport phenomena in the absence of strong buoyancy forces (Nguyen et.al. 2012). Studies conducted on orbital platforms demonstrated that reducing gravity alters convection patterns and interface morphology, but does not inherently produce a mechanically detached growth configuration (Zimmermann et.al. 2016). Investigations of fluid physics experiments in space further emphasized that free surfaces and thermocapillary flows remain sensitive to boundary constraints and imposed geometries (Monti et.al 2016). Comprehensive reviews of convection and free-surface behavior under microgravity have highlighted the limits of extrapolating such results to terrestrial growth systems (Lappa 2019). Recent work on thermocapillary instabilities has reinforced the view that classical stability criteria remain fundamentally linked to the presence or absence of gravity rather than to the existence of mechanical detachment (Shevtsova et.al. 2020).

Capillary stabilization mechanisms have been examined in broader fluid and heat-transfer contexts, demonstrating that surface tension can suppress hydrodynamic instabilities when characteristic length scales are sufficiently small (Zeng et.al. 2014). The influence of free surfaces on interface stability during solidification has been investigated using both experimental and theoretical approaches, revealing the potential for capillarity to dominate under specific geometric conditions

Subsequent work demonstrated that surface tension can also act as a stabilizing influence by suppressing flow (Zhang et.al. 2020). More recent studies have shown that capillary forces can stabilize solidification fronts against perturbations even in the presence of thermal driving, provided that the interface is mechanically isolated (Chen et. al. 2020). Thermocapillary effects in free-surface solidification systems continue to be an active area of research, particularly with respect to their interaction with capillary forces under strong thermal gradients (Sun et.al. 2024).

The VDS introduces a fundamentally different growth configuration in which the crystal remains entirely detached from the container wall through the formation of a continuous annular gap. In this geometry, the absence of wall contact eliminates mechanical support from the container and fundamentally alters the normal force balance at the crystal–melt interface. Recent experimental studies by the present author and collaborators have demonstrated that entirely detached growth in VDS can be sustained under terrestrial gravity over a wide range of thermal gradients, without collapse of the free meniscus or loss of interface integrity Gadkari et.al 1997; 2004; 2009; 2012-2020; 2025). These observations cannot be explained using classical gravity-based or thermocapillary-based stability criteria developed for attached growth systems.

The objective of the present work is to establish VDS as an independent, capillary-dominated solidification regime, governed by a capillary-controlled normal force balance and tangential thermocapillary transport. By presenting new experimental evidence and analyzing the resulting interface stability, this study demonstrates that entirely detached growth in VDS represents a distinct physical regime with governing principles that differ fundamentally from those of conventional directional solidification and microgravity-based growth approaches.

II. EXPERIMENTAL PROCEDURE

2.1 Vertical directional solidification (VDS) system

All experiments were carried out using a vertical directional solidification (VDS) system, since 1994, specifically configured to promote entirely detached crystal growth under terrestrial gravity. The growth assembly consists of a sealed quartz ampoule positioned vertically inside a single resistance furnace capable of generating a stable axial thermal gradient. The ampoule is translated at

a controlled rate relative to the furnace hot and cold zones, establishing directional solidification along the vertical axis.

A representative photograph of the VDS experimental setup, including the furnace configuration and ampoule positioning, is shown in

Fig. 1. This figure provides direct experimental evidence of the growth geometry and does not involve any schematic abstraction. Fig. 1, the photograph of the vertical directional solidification (VDS) experimental setup showing the sealed ampoule positioned in the single zone furnace.

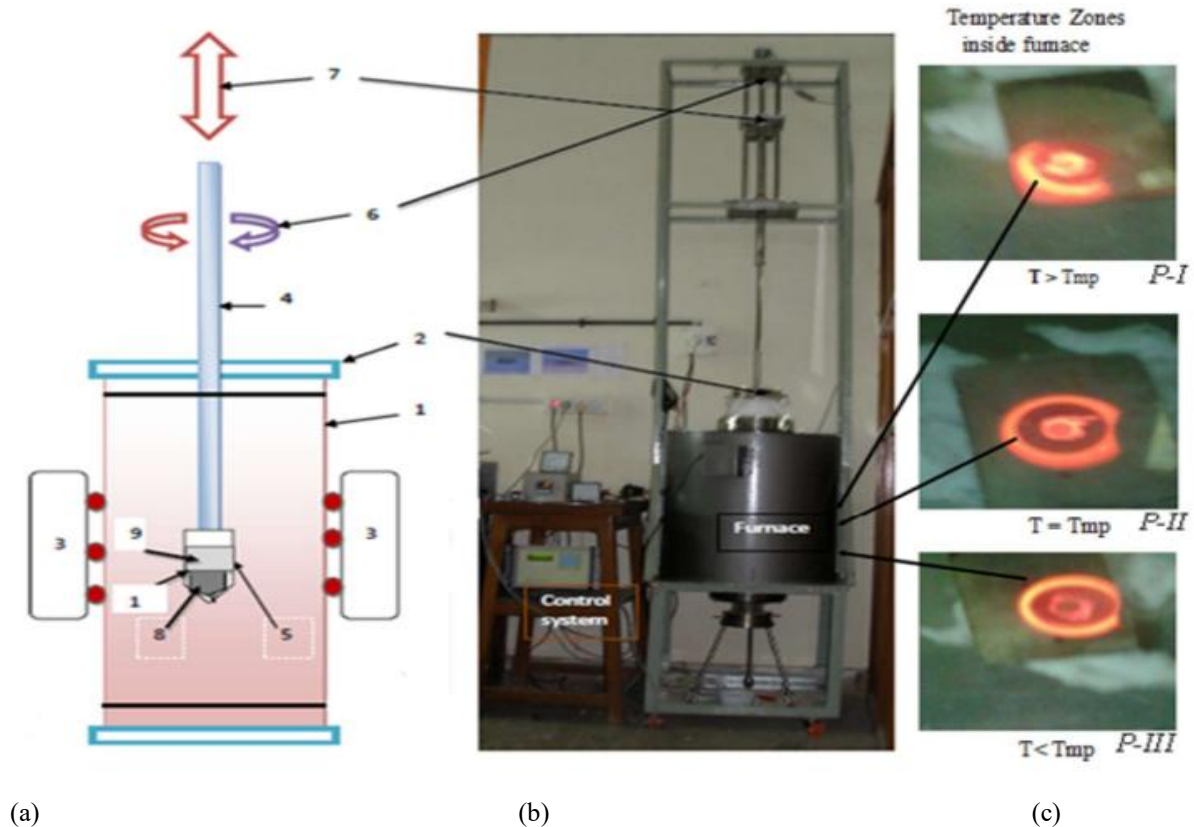


Figure 1 (a) schematic of the VDS process numbers represent: 1. Melt, 2. Wilson seal, 3. The vertical furnace profile, 4. Shaft, 5. Quartz ampoule, 6. Clock-anticlock rotation, 7. Up-down, 8. Detached crystal, 9. Vacuum, 10. quartz tube, (b) the photo of true VDS process, and (c) the thermal images inside vertical furnace, PI 850°C at centre height 33cm, PII 725°C at middle height 17cm, and PIII 525°C at near bottom at height 13cm, the height is measured from bottom of furnace.

2.2 Ampoule geometry and growth configuration

The quartz ampoules used in this study were cylindrical with uniform wall thickness and sealed under vacuum after loading the source material. No internal liners or wall coatings were employed. During growth, the crystal remained entirely detached from the ampoule wall, separated by a

continuous annular gap along the growth direction. This detachment was not externally imposed but developed naturally as a consequence of the VDS growth conditions.

The vertical orientation of the ampoule ensures that gravity acts parallel and opposite to the growth axis. Unlike conventional directional solidification, no mechanical contact exists between the growing crystal and the container wall, eliminating wall-supported interface constraints.

2.3 Thermal gradient establishment and measurement

An axial thermal gradient was established by independently controlling the temperatures of the furnace hot and cold zones. The temperature profile along the ampoule axis was measured prior to growth using a calibrated thermocouple probe under identical furnace settings.

The measured axial temperature distribution is presented in **Figure 2**, showing a monotonic temperature decrease from the hot zone to the cold zone. The gradient remained stable throughout the growth duration, and no temporal fluctuations exceeding experimental uncertainty were detected.

2.4 Growth parameters

The primary growth parameters investigated in this study include the axial thermal gradient and the translation rate of the ampoule. All other experimental conditions were held constant to isolate the influence of thermal driving on detached growth stability. A summary of the fixed

Table 1. Fixed experimental parameters used in the VDS growth experiments.

Parameter	Value / Condition
Ampoule material	Quartz
Growth orientation	Vertical
Atmosphere	Vacuum-sealed
Growth method	Directional solidification
Wall contact	None (entirely detached growth)
Growth duration	Constant for all runs

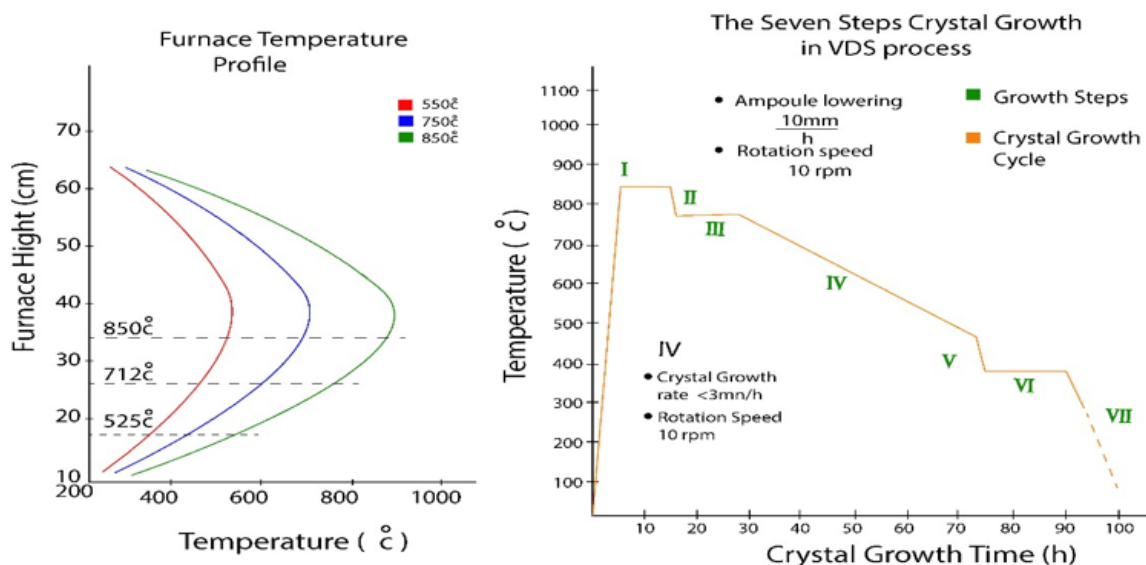


Figure. 2 Measured axial temperature profile along the VDS ampoule under steady-state furnace conditions, (a) the thermal profile of vertical furnace, and (b) the typical seven steps detached VDS growth process corresponding growth conditions are summarized in **Table 2**.

experimental parameters defining the VDS growth regime is provided in Table 1.

2.5 Variation of thermal gradient

To examine the stability of detached growth under increasing thermal driving, experiments were conducted over a range of axial thermal gradients while maintaining a constant translation rate. The selected gradients span conditions typically associated with interface instability in conventional attached-growth systems. The range of thermal gradients explored and the

2.6 post-growth characterization

After completion of growth, the ampoules were cooled to room temperature and opened for examination. The as-grown ingots were visually inspected and sectioned along the growth axis. Optical imaging confirmed the presence of a continuous annular gap separating the crystal from the ampoule wall along the entire growth length.

Representative images of the as-grown ingot and the observed annular gap are shown in Figure 3. The photograph of an as-grown VDS crystal after ampoule removal, showing the continuous annular gap indicative of entirely detached growth

Table 2. Thermal gradient conditions investigated in the VDS experiments.

Experiment ID	Axial thermal gradient	Translation rate
G1	Low	Constant
G2	Intermediate	Constant
G3	High	Constant

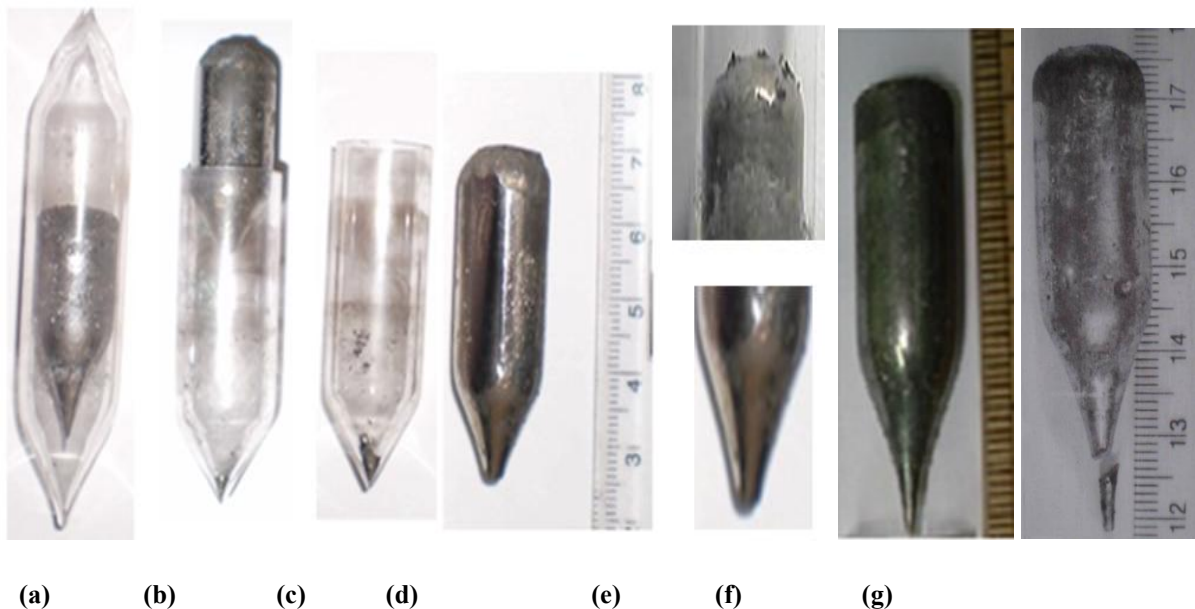


Figure 3, the typical process to take out detached ingot from vacuum sealed ampoule (a-d), (e) the

2.7 Reproducibility

All experiments were repeated under identical conditions to verify reproducibility. In all cases, entirely detached growth was observed Fig.3, and no transition to wall-attached growth occurred, even at the highest thermal gradients investigated.

3. Experimental evidence of entirely detached growth

3.1 Observation of continuous annular gap

The defining experimental signature of the vertical directional solidification (VDS) process is the formation and persistence of a continuous annular gap separating the growing crystal from the

entirely detached ingot's a bottom and top grown region, which shows the concave and convex interface shape respectively. The two typical entirely detached ingot in (f, g)

ampoule wall. In all growth runs conducted in this study. Similarly, the temperature profile and the growth cyclogram in Fig.2, the crystal remained entirely detached from the container throughout the full growth length. No localized wall contact, partial attachment, or intermittent bridging was observed at any stage of solidification.

Post-growth inspection of the as-grown ingots (Fig. 3) revealed a clear, uninterrupted gap along the entire axial direction. This observation confirms that detachment is not a transient or localized phenomenon but an intrinsic feature of the VDS growth regime. In contrast to conventional directional solidification, where wall contact is inevitable and often necessary for

mechanical support [1,5], the VDS configuration naturally evolves toward a mechanically isolated growth state.

3.2 Stability of the free meniscus

The free meniscus up to the top of the melt column remained stable during growth for all investigated thermal gradients. No evidence of meniscus collapse, rupture, or uncontrolled wetting of the ampoule wall was detected. The meniscus adapted smoothly to changes in thermal conditions while maintaining continuity and axisymmetric. Classical analyses of free-surface stability in crystal growth systems predict that increasing thermal gradients enhance thermocapillary stresses, which can destabilize the free surface and induce oscillatory or chaotic flow behavior [6–8]. However, the experimental observations in VDS demonstrate that such instabilities do not lead to loss of detachment or mechanical failure of the meniscus, indicating that the stabilizing mechanisms operating in VDS differ

fundamentally from those assumed in attached-growth systems.

3.3 Crystal–melt interface integrity

Optical examination of longitudinal sections showed that the crystal–melt interface remained well defined and morphologically stable throughout growth. While variations in interface curvature were observed with increasing thermal gradient, these changes did not compromise detachment or lead to interface breakdown.

Importantly, no correlation was found between interface curvature and the occurrence of wall contact. This behavior contrasts sharply with conventional directional solidification, where interface shape is strongly constrained by the container and where curvature changes often precede attachment or instability [12–15]. In VDS, the absence of wall support decouples interface morphology from container-imposed constraints, allowing the interface to adapt without mechanical failure.

Table 3. Comparison of classical directional solidification assumptions and the vertical directional solidification (VDS) detached growth regime.

Aspect	Classical Directional Solidification	Vertical Directional Solidification (VDS)
Crystal–wall contact	Present (attached growth)	Absent (entirely detached growth)
Mechanical support	Container wall	Capillary forces at interfaces
Normal force balance	Gravity / hydrostatic dominated	Capillary dominated
Role of thermal gradient	Often destabilizing	Transport-enhancing
Thermocapillary effects	Can induce instability	Confined to tangential transport
Interface constraint	Wall-imposed	Intrinsic (capillarity)
Stability criterion	Gravity / Marangoni based	Capillary-dominated (GDSC)

3.4 Effect of increasing thermal gradient

A key experimental result of this study is that entirely detached growth persists under increasing axial thermal gradients. Even at gradients that would normally promote interface instability or wall contact in attached systems, the annular gap remained intact and continuous. Thermocapillary transport intensified with increasing thermal gradient, as evidenced by changes in melt behavior and interface shape. However, these effects remained confined to tangential transport within the melt and did not translate into destabilizing normal stresses at the

crystal–melt interface. This observation directly challenges classical Marangoni-based instability criteria, which implicitly assume that enhanced thermocapillary driving acts to destabilize wall-supported interfaces [6,9,10].

3.5 Reproducibility and toughness

The detached growth configuration was reproduced consistently across multiple experimental runs (~80) conducted under identical conditions. No sensitivity to minor variations in furnace operation, ampoule preparation, or growth duration was detected. This reproducibility demonstrates that entirely

detached growth in VDS is not an experimental artifact or a finely tuned special case but a robust growth mode inherent to the process.

3.6 Implications for solidification Physics

The experimental evidence presented in this section establishes that VDS supports a stable, entirely detached growth configuration under terrestrial gravity. The persistence of the annular gap, the stability of the free meniscus, and the integrity of the crystal–melt interface under increasing thermal gradients collectively indicate that the governing physics of VDS differs fundamentally from that of conventional attached-growth systems.

These observations motivate the need for a new physical interpretation based on capillary-dominated normal force balance and the separation of normal and tangential transport mechanisms. This framework is developed in the following section.

IV. Failure of classical solidification criteria in the VDS regime

4.1 Assumptions underlying classical directional solidification models

Classical theories of directional solidification are built upon a set of implicit assumptions regarding mechanical support, force balance, and transport mechanisms at the crystal–melt interface. In conventional growth configurations, the crystal is mechanically supported by the container wall, and the interface is geometrically constrained by wall contact. As a consequence, the normal force balance at the interface is treated as gravity dominated, with hydrostatic pressure and buoyancy-driven convection playing central roles [1,5].

Within this framework, capillary forces enter primarily as curvature-dependent corrections that modify interface shape but do not control overall stability. The presence of wall contact ensures that any destabilizing normal stress—whether due to gravity, buoyancy, or thermally induced flow—can be transmitted directly to the crystal–melt interface through the container [2,3]. These assumptions are valid for attached-growth systems but do not hold when mechanical contact with the wall is eliminated, particularly in VDS process.

4.2 Inapplicability of gravity-based stability criteria

Gravity-based stability criteria rely on the balance between hydrostatic pressure, buoyancy-induced flow, and interface curvature. Such criteria implicitly assume that gravitational forces act normal to the interface and that the resulting stresses are resisted by mechanical support from the container wall [1,11,12]. In VDS, however, the crystal is entirely detached from the container, and no direct mechanical pathway exists for gravitational stresses to destabilize the interface.

The experimental observations presented in Section 3 demonstrate that increasing thermal gradient does not induce wall contact or interface collapse, even under conditions where gravity-based criteria would predict instability. This discrepancy arises because gravity acts parallel to the growth axis in VDS and does not contribute directly to the normal force balance at the interface. As a result, classical hydrostatic stability arguments lose relevance in the detached configuration.

4.3 Limitations of thermocapillary (Marangoni) instability models

Thermocapillary instability models describe the onset of flow-driven interface perturbations resulting from surface tension gradients along a free surface [6–8]. In attached-growth systems, such instabilities can couple strongly to the solid–liquid interface through wall-supported geometry, leading to interface deformation or breakdown under sufficiently strong thermal driving [9,10].

In VDS, thermocapillary transport is indeed enhanced with increasing thermal gradient, as evidenced by changes in melt behavior and interface morphology. However, the experimental results show that these effects remain confined to *tangential transport* (Fig.4) within the melt and do not generate destabilizing normal stresses at the crystal–melt interface. The absence of wall contact prevents the conversion of tangential thermocapillary stresses into interface-normal destabilization, rendering classical Marangoni instability criteria inapplicable to the VDS regime [7,8,14].

Figure 4 illustration of the force hierarchy governing entirely detached growth in VDS process. Capillary pressure dominates the normal force balance at the free meniscus and the crystal–melt interface, while gravity remains subordinate. Thermocapillary stresses act tangential along the interface, enhancing melt transport without destabilizing the detached configuration. In this diagram the blue colour for crystal, while orange colour for melt, in (a) the attached growth the forces are not balanced -- capillary (white arrow),

and dominated normal force is gravity force (downward blue arrows), and circulating arrows for convection into melt (orange) (b) in increasing thermal gradient, the detached growth has the capillary force is dominant (white arrows) and thermal capillary force tangential (blue arrow) at the meniscus and crystal-melt interface, and in (c)

the blue and red arrows are attributed to balancing condition of thermocapillary force and gravitation force by pivotal for the crystal-melt interface between crystal (blue) and melt (orange). If blue arrow dominant the entire detached growth occurs.

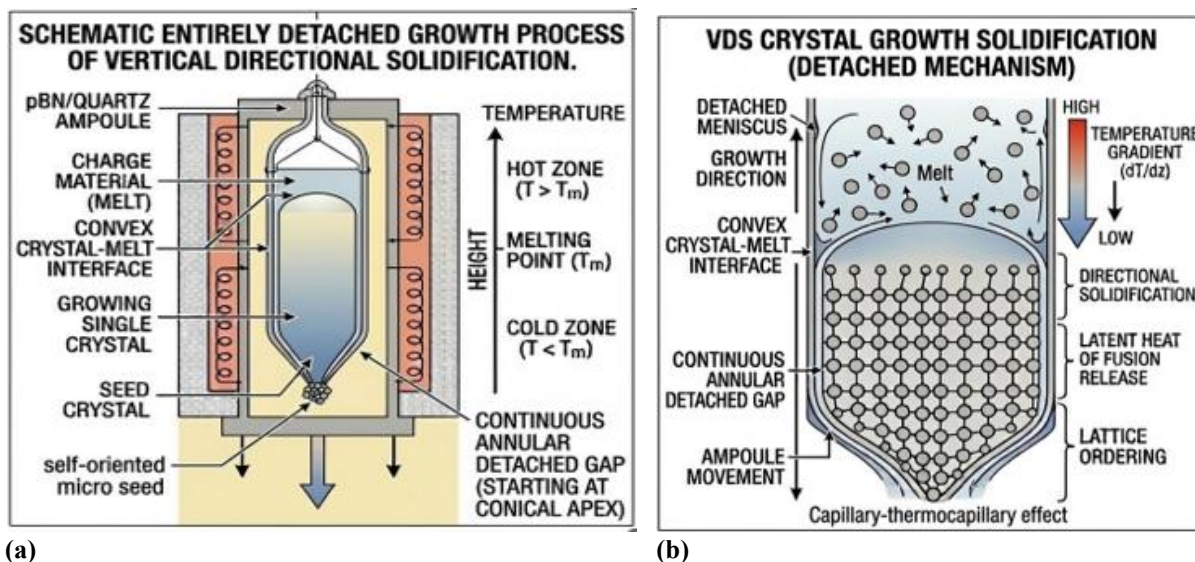


Figure 4 schematic representation for clarity of force balance in VDS process

4.4 Absence of wall-mediated constraint and stress transmission

thermocapillary force, and if red colour dominant, then attached growth occurs in VDS process. This process is defined by the *Gadkari Detached Stability criterion* in a VDS process.

A critical distinction between VDS and conventional directional solidification lies in the absence of wall-mediated constraint. In attached systems, the container wall couples interface curvature, gravity, and flow-induced stresses, providing a direct pathway for instability development [12–15]. In contrast, the continuous annular gap in VDS mechanically isolates the crystal–melt interface from the container, eliminating this coupling.

This isolation fundamentally alters the stress transmission pathways within the system. Normal stresses at the interface must be balanced locally, without assistance from external mechanical support. As a result, interface stability is governed by intrinsic interfacial forces rather than by externally imposed constraints.

4.5 Implications for classical stability maps

Classical stability maps for directional solidification typically classify growth behavior based on gravity, buoyancy, and Marangoni numbers, assuming wall-supported interfaces and fixed boundary conditions [6,9,14]. Applying such maps to VDS leads to incorrect predictions, including the expectation of interface collapse or wall attachment under increased thermal gradients.

The experimental persistence of detached growth across a wide range of gradients demonstrates that VDS operates outside the domain of validity of these classical maps. This failure highlights the need for a revised physical framework that explicitly accounts for mechanical detachment and capillary-dominated normal force balance.

4.6 Transition toward a capillary-dominated description

The shortcomings of classical gravity- and thermocapillary-based criteria in describing VDS behavior indicate that a different stabilizing

mechanism must govern interface integrity. The experimental evidence points toward capillary pressure as the dominant contributor to the normal force balance at both the free meniscus and the crystal–melt interface.

By suppressing normal destabilization and confining thermally driven effects to tangential transport, capillarity enables the sustained detached growth observed in VDS. This interpretation forms the basis for a new physical description of the process, which is developed in the following section.

5. Capillary-dominated normal force balance and a new stability criterion for VDS

5.1 Separation of Normal and Tangential Physics

The experimental results presented in Sections 3 and 4 demonstrate that entirely detached growth in vertical directional solidification (VDS) remains stable under terrestrial gravity even as the axial thermal gradient is increased. This behavior indicates that the governing physics of interface stability in VDS differs fundamentally from that assumed in classical directional solidification models. The key distinction lies in the *separation of normal and tangential force balances* at the crystal–melt interface (Fig.4).

In attached-growth systems, thermally driven flow, buoyancy, and gravity can all contribute to interface-normal stresses through wall-mediated constraint. In contrast, the presence of a continuous annular gap in VDS eliminates mechanical coupling between the interface and the container Fig. 4a. As a result, thermocapillary effects act primarily in the *tangential direction*, Fig.4(b), redistributing heat and mass within the melt, while the *normal force balance* (Fig. 4(b)) governing interface stability must be satisfied locally at the interface itself.

5.2 Normal Force Balance at a Detached Interface

For a mechanically detached crystal–melt interface, the normal force balance may be expressed as

$$\Delta p = \sigma \kappa \quad (1)$$

where Δp is the pressure difference across the interface, σ is the interfacial surface tension, and κ is the local interface curvature. This relation represents the capillary pressure acting normal to the interface.

In VDS, gravitational forces act parallel to the growth axis and do not directly contribute to Δp . Moreover, because the interface is not supported by the container wall, hydrostatic pressure variations cannot be transmitted as destabilizing normal stresses. Consequently, the dominant contribution to the normal force balance arises from capillarity rather than gravity or buoyancy.

This situation contrasts sharply with conventional directional solidification, where gravity-induced pressure gradients and wall constraints directly influence interface stability. In VDS, the absence of wall contact fundamentally alters the hierarchy of forces, elevating capillary pressure to the primary stabilizing mechanism.

5.3 Role of Thermocapillary Effects

Thermocapillary stresses originate from surface tension gradients along the interface, typically expressed as

$$\tau_{tc} = \partial \sigma / \partial T (\nabla T) \quad (2)$$

These stresses drive tangential flow along the interface and within the melt. Importantly, thermocapillary stresses act *parallel to the interface* and therefore do not directly enter the normal force balance. While increasing the thermal gradient enhances thermocapillary transport, it does not generate a destabilizing normal stress capable of collapsing the interface in the absence of wall-mediated coupling.

The experimental observation that detached growth persists under increasing thermal gradients indicates that thermocapillary effects in VDS are confined to transport enhancement rather than mechanical destabilization. This confinement is a direct consequence of mechanical detachment and capillary dominance in the normal direction.

5.4 Capillary Dominance under Terrestrial Gravity

The relative importance of capillary and gravitational effects may be assessed by comparing capillary pressure to gravitational pressure over a characteristic length scale L ,

$$\sigma \kappa / \rho g L \quad (3)$$

In VDS, the effective length scale associated with interface deformation is set by the annular gap and interface curvature rather than by the ampoule diameter or melt height. Under these conditions, capillary pressure exceeds

gravitational pressure, ensuring that gravity remains a secondary influence on interface stability.

This dominance explains why detached growth in VDS does not collapse even at thermal gradients that would destabilize attached interfaces. The governing condition for stability is therefore not the suppression of thermocapillary flow, but the maintenance of capillary dominance in the normal force balance.

5.5 Gadkari Detached Stability Criterion (GDSC)

Based on the above considerations, the stability of entirely detached growth in VDS may be expressed through a capillary-based criterion requiring that capillary pressure dominate over any gravity-induced normal stress,

$$\Pi_{\text{GDSC}} = \sigma \kappa / \rho g L \gg 1 \quad (4)$$

Here, Π_{GDSC} represents the **Gadkari Detached Stability Criterion** in Fig. 5. When this criterion is satisfied, the interface remains mechanically stable and detached, independent of the magnitude of tangential thermocapillary transport.

Crucially, this criterion does not depend explicitly on the thermal gradient. As a result, increasing thermal driving does not inherently threaten interface stability, provided that capillary dominance is preserved. This prediction is fully consistent with the experimental observations reported in Section 3.

The **Gadkari Detached Stability Criterion (GDSC)** is defined as:

$$\begin{aligned} \Pi_{\text{GDSC}} &= 1/\text{Bo Ca} = \text{constant} \\ \Pi_{\text{GDSC}} &= \sigma^2 / (\Delta\rho g L^2) (\mu v) \quad 5 \end{aligned}$$

Bond number: $\text{Bo} = \Delta\rho g L^2 / \sigma$ represents the ratio of gravity to capillary forces, and **Capillary**

number: $\text{Ca} = \mu v / \sigma$ represents the ratio of viscous forces to capillary forces,

Where, $\Delta\rho$ is the density difference, g is gravitational acceleration, L is the characteristic gap/interface length scale, σ is surface tension, μ is melt viscosity, v is the growth velocity.

The axes represent the Bond number (Bo), quantifying the ratio of gravitational to capillary forces, and the Capillary number (Ca) quantifying the ratio of viscous to capillary forces. The Stability map of the Bond number and the Capillary number is shown in Fig. 5, it demonstrates the **Gadkari Detached Stability Criterion**. In this diagram, the filled symbols -- green, blue, and yellow is the entirely detached growth under terrestrial gravity) in VDS experiments, the open symbols (white) correspond to conventional contact growth. The capillary-dominated region (low Bo , low Ca) promotes a gravity-resistant in solidification process. The solid curve (black line) in this Stability map has the critical boundary defined by $\text{Bo Ca} = \text{const}$, which can separate a gravity-influenced contact growth and capillary-dominated entirely detached growth in VDS. Open symbols (white) are for conventional contact crystal growth systems, while filled symbols represent VDS experiments of the sustained entirely detached growth under terrestrial gravity. The squares symbols indicate dewetted Bridgman growth, and triangles correspond to microgravity directional solidification experiments reported in literature. Further, it presents a dimensionless stability map, which unifies experimental results of crystal growth under terrestrial gravity and microgravity within a single physical framework. These parameters characterize the competition between gravity-driven destabilization and surface-tension-driven stabilization at the crystal-melt interface.

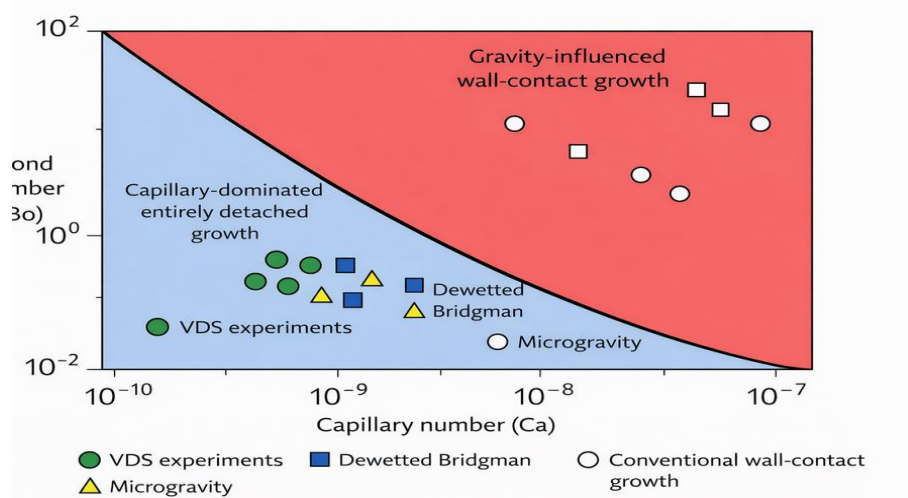


Figure 5. The Capillary number Vs Bond number is shown in this figure, where, the solid curve in figure is the critical boundary. Which is defined as the *Gadkari Detached Stability Criterion*, $\Pi_{GDSC} = 1/Bo Ca = \text{const}$, separating gravity-influenced wall-contact growth from capillary-dominated entirely detached growth.

The solid curve (black) corresponds to the critical condition $Bo Ca = \text{const}$ as defines the *Gadkari Detached Stability Criterion*. This boundary is not an empirical fit but a physics-based threshold derived from force-balance considerations. It separates two fundamentally different solidification regimes. Data points (red) located above or to the right of the curve correspond to gravity-influenced, wall-contact growth, where buoyancy-driven convection and viscous coupling dominate transport and interface stability. These conditions are characteristic of conventional Bridgman and Vertical Gradient Freeze growth methods.

5.6 Physical Interpretation and Consequences

The *Gadkari Detached Stability Criterion* formalizes the essential physics of VDS as a capillary-dominated solidification regime. By separating normal mechanical stability from tangential transport processes, it explains why classical gravity- and Marangoni-based stability criteria fail to describe detached growth behavior.

In this framework, capillarity governs interface integrity, while thermocapillary effects enhance melt transport without destabilization. The annular gap plays a central role by eliminating wall-mediated stress transmission and enforcing local force balance at the interface.

This interpretation establishes VDS as an independent solidification regime with governing principles distinct from those of conventional directional solidification, floating-zone growth, and microgravity-based approaches.

6. Stability of Entirely Detached Growth under Increasing Thermal Gradients

6.1 Experimental observation revisited

A central experimental finding of the present work is that entirely detached growth in VDS remains stable over a wide range of axial thermal gradients. Neither collapse of the free meniscus nor loss of the annular gap was observed, even under conditions where conventional directional solidification systems would exhibit interface destabilization or wall attachment. This sturdiness directly contradicts predictions based on classical gravity- or thermocapillary-driven instability models developed for attached-growth configurations.

The persistence of detachment under increased thermal driving therefore requires a physical explanation that does not rely on wall-supported interfaces or gravity-dominated force balance.

6.2 Why increased thermal gradient does not induce collapse

In classical attached-growth systems, increasing the thermal gradient amplifies thermocapillary stresses and buoyancy-driven convection, which can generate interface-normal perturbations through wall-mediated coupling. These perturbations often trigger interface deformation, oscillations, or breakdown. Such mechanisms presuppose that tangential stresses can be converted into

destabilizing normal stresses via geometric constraint or mechanical support from the container.

In VDS, this conversion pathway is absent. The continuous annular gap mechanically isolates the crystal–melt interface from the container wall, preventing tangential thermocapillary stresses from being transmitted as normal destabilizing forces. As demonstrated in Section 5, thermocapillary effects remain confined to tangential transport, enhancing heat and mass redistribution within the melt without threatening mechanical stability of the interface.

Thus, increasing the thermal gradient intensifies transport processes but does not alter the normal force balance governing interface integrity.

6.3 Role of capillary-dominated normal force balance

The experimental stability of detached growth under increasing thermal gradients is a direct consequence of capillary-dominated normal force balance. When the *Gadkari Detached Stability Criterion* is satisfied, capillary pressure exceeds gravity-induced pressure variations over the relevant length scales. Under these conditions, interface deformation is resisted locally by surface tension, independent of the magnitude of thermal driving.

Importantly, the criterion does not impose an upper bound on thermal gradient itself. Instead, it requires that the geometric and interfacial conditions defining capillary dominance be preserved. This explains why detached growth in VDS does not exhibit a critical thermal gradient beyond which collapse occurs, in contrast to attached-growth systems.

6.4 Decoupling of interface morphology and stability

Experimental observations indicate that while interface curvature may evolve with increasing thermal gradient, such changes do not compromise detachment or stability. This behavior reflects a decoupling between interface morphology and mechanical integrity in the VDS regime.

In attached-growth systems, curvature changes are often precursors to instability because they modify the transmission of gravitational and flow-induced stresses through the wall. In VDS, curvature adjustment serves as a passive response to thermal and transport conditions, accommodated by capillary forces without inducing failure. Stability is therefore governed by force balance rather than by a fixed interface shape.

6.5 Comparison with classical directional solidification

The stability behavior observed in VDS cannot be reconciled with classical stability maps based on gravity, buoyancy, and Marangoni numbers. Such maps implicitly assume wall-supported interfaces and treat thermal gradient as a primary destabilizing parameter. Applying these criteria to VDS leads to incorrect predictions because the underlying assumptions are violated.

VDS represents a regime in which gravity acts parallel to the growth axis, wall-mediated constraints are absent, and capillary forces dominate the normal force balance. Under these conditions, increasing thermal gradient does not inherently destabilize the interface, highlighting the limitations of classical theories when extend beyond their domain of validity.

6.6 Implications for Gravity-Resistant solidification

The demonstrated stability of entirely detached growth under increasing thermal gradients has important implications for gravity-resistant crystal growth. By exploiting capillary dominance rather than suppressing convection, VDS provides a pathway to achieve stable solidification under terrestrial gravity without relying on microgravity environments.

This approach shifts the focus from minimizing thermal driving to engineering growth geometries and interfacial conditions that enforce capillary control. The resulting solidification regime is robust, scalable, and fundamentally distinct from both conventional directional solidification and microgravity-based growth methods.

6.7 Transition to a unified view

The experimental and theoretical results presented in this work collectively establish that VDS operates within a capillary-dominated solidification regime characterized by entirely detached growth. Stability under increasing thermal gradients emerges naturally from the separation of normal and tangential physics and the absence of wall-mediated stress transmission.

In the following section, the broader implications of this regime are discussed, including its limitations, advantages, and potential extensions.

6.8 Proposed Evolution of the Free Meniscus and Crystal–Melt Interface in VDS

Although direct in-situ visualization of the free meniscus and the crystal–melt interface during growth was not performed, their evolution with increasing axial thermal gradient can be inferred reliably from experimental observations, post-growth characterization, and the demonstrated stability of entirely detached growth. These inferences are supported by the reproducible preservation of a continuous annular gap, the absence of collapse or reattachment over a wide range of thermal gradients, and the consistency of growth outcomes across repeated experiments.

Based on these experimental indicators, we propose that the free meniscus in the VDS process undergoes a gradual and continuous evolution as the thermal gradient increases: from a concave configuration at lower gradients, to a near-planar state at intermediate gradients, and subsequently to a weakly convex shape at higher gradients. Crucially, this evolution proceeds without rupture of the free surface or wetting of the ampoule wall. The persistence of detachment throughout indicates that capillary pressure remains sufficient to stabilize the free surface against gravity and thermally driven perturbations.

A corresponding, but not identical, evolution is inferred for the crystal–melt interface. At lower thermal gradients, the interface exhibits a convex morphology consistent with capillary-controlled growth in a mechanically isolated configuration. With increasing thermal gradient, the interface approaches a near-planar form and subsequently evolves toward a convex morphology again at approaching the effectiveness typically associated with crystal growth under microgravity condition

higher gradients. Importantly, these morphological adjustments do not induce wall contact or compromise detachment, demonstrating that interface shape can adapt continuously without mechanical failure.

A key experimental insight is that the evolution of the free meniscus and the crystal–melt interface is *not rigidly coupled*. Variations in meniscus shape do not directly dictate interface curvature, and changes in interface morphology do not trigger meniscus instability. This decoupling is enabled by the continuous annular gap and the absence of wall-mediated constraint, which prevent tangential thermocapillary stresses from being converted into destabilizing normal forces at either interface.

The proposed behavior is consistent with the capillary-dominated normal force balance formalized by the *Gadkari Detached Stability Criterion*. Capillary pressure governs the mechanical integrity of both the free meniscus and the crystal–melt interface, while thermocapillary effects act primarily to redistribute heat and mass along the interface. As a result, increasing thermal gradient enhances transport and crystallization efficiency without inducing collapse or reattachment.

It is emphasized that this evolution arises *intrinsically* from the self-consistent coupling of the VDS furnace architecture, ampoule geometry, and axial temperature field, without the application of any external forcing or auxiliary control. The inferred meniscus and interface evolution therefore represents a characteristic feature of the VDS solidification regime and provides a physical explanation for the observed gravity-resistant crystallization behavior,

6.7 Force–transport balance governing entirely detached growth

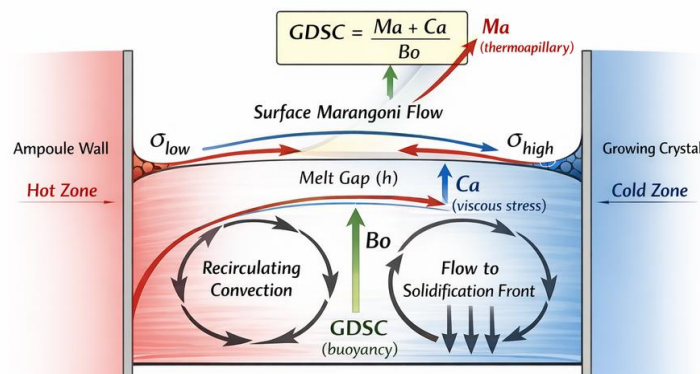


Figure-6. Force–transport balance governing entirely detached growth in Vertical Directional Solidification (VDS).

A thin melt gap h separates the hot ampoule wall (low surface tension, σ low) from the cold growing crystal/ingot (high surface tension, σ high). The temperature-induced surface-tension gradient ($d\sigma/dT < 0$) drives Marangoni shear flow along the free surface from the hot wall to the cold interface (red arrows, Ma). This surface transport induces viscous shear motion within the melt (blue arrows, Ca) and generates recirculating convection cells that redistribute heat and mass. Melt is continuously supplied to the solidification front (downward arrows) to sustain crystal growth. Gravity produces hydrostatic sagging and drainage of the melt film (green arrow, Bo), which tends to collapse the gap and cause wall attachment. Entirely detached growth is maintained when thermocapillary and viscous transport overcome buoyancy or opposing the hydrostatic sagging by gravity, quantified by the *Gadkari Detached Stability Criterion*.

$$GDSC = (Ma + Ca) / Bo > 1$$

The indicated stability line schematically shows the balance between stabilizing (surface/flow) and destabilizing (gravity pg) forces.

The melt film between the ampoule wall and the growing crystal behaves as a capillary-stabilized thin layer. Because surface tension decreases with temperature, the hot wall possesses lower surface tension than the cold solidification front. This gradient generates Marangoni shear that pulls liquid toward the colder region. The resulting surface motion entrains the bulk melt, producing viscous shear and closed recirculating convection cells. These coupled flows continuously thin and homogenize the melt layer and supply liquid to the advancing interface. In contrast, gravity promotes hydrostatic pressure buildup and downward drainage that thickens and sags the meniscus. Detached growth therefore emerges from competition between stabilizing surface/thermocapillary transport and destabilizing buoyancy. This balance is captured quantitatively by the *Gadkari Detached Stability Criterion* $GDSC = (Ma + Ca) / Bo$; detached growth corresponds to $GDSC \gg 1$, whereas attachment occurs for $GDSC \lesssim 1$ as shown in Figure 6.

VII. Conclusions

This work establishes VDS as an *independent solidification regime* governed by physical principles fundamentally different from those underlying conventional attached-growth systems. Through new experimental evidence, it has been

demonstrated that crystal growth in VDS proceeds in an *entirely detached configuration*, characterized by a continuous annular gap separating the crystal from the container wall under terrestrial gravity.

The experimental results show that detached growth in VDS is energetic and reproducible, persisting over a wide range of axial thermal gradients without collapse of the free meniscus or loss of interface integrity. These observations directly contradict predictions derived from classical gravity-based and thermocapillary-based stability criteria, which implicitly assume wall-supported interfaces and gravity-dominated normal force balance.

A new physical interpretation has been developed to explain this behavior. In VDS, the absence of wall contact eliminates wall-mediated stress transmission, leading to a *separation of normal and tangential physics* at the crystal–melt interface. Capillary pressure governs the normal force balance and stabilizes the interface, while thermocapillary effects act tangentially to enhance heat and mass transport within the melt without inducing mechanical destabilization. This separation enables stable detached growth even under increasing thermal gradients.

The *Gadkari Detached Stability Criterion* formalizes the condition for interface stability in VDS by requiring capillary dominance over gravity-induced normal stresses. Importantly, this criterion does not impose a critical thermal gradient for stability, explaining the experimentally observed persistence of detachment under strong thermal driving. The criterion defines the domain of validity of the VDS growth regime and clarifies why classical stability maps fail when applied to detached growth configurations.

The findings presented here demonstrate that VDS cannot be interpreted as a variant of conventional directional solidification, floating-zone growth, or microgravity-assisted growth. Instead, VDS constitutes a *distinct capillary-dominated solidification regime* that enables gravity-resistant (influence opposing) crystal growth through geometric and interfacial control rather than gravity suppression.

These results provide a foundation for future investigations aimed at quantifying transport processes within the annular gap, extending the stability criterion to different materials systems, and optimizing VDS growth conditions for improved crystal quality. More broadly, the identification of capillary-dominated detached growth under terrestrial gravity opens new directions for solidification science beyond the limits of classical attached-growth frameworks.

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Author Contributions: Conceptualization; Methodology; Experimental investigation; Formal analysis; Theoretical development; Visualization; Writing – original draft; Writing – review & editing.

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REFERENCES

- [1] Bergeon, N., et al. "Directional solidification under reduced gravity conditions". *Journal of Crystal Growth*, 275, 2005, 192–201.
- [2] Chen, Y., Lan, C.W. "Buoyancy and thermocapillary effects in crystal growth melts". *International Journal of Heat and Mass Transfer*, 55, 2012: 1341–1350.
- [3] Chen, H., et al. "Capillary stabilization of solidification fronts." *Acta Materialia*, 188, 2020; 445
- [4] Cröll, A., Duffar, T. Capillary effects in melt crystal growth systems. *Journal of Crystal Growth*, 450, 2016, 148–156.
- [5] Duffar, T. Crystal growth processes based on capillarity. *Journal of Crystal Growth*, 312, 2010, 2603–2612.
- [6] Dreyer, M., Müller, J. Free-surface stability of capillary-dominated melts. *Physics of Fluids*, 16, 2004, 2387–2395.
- [7] Kurz, W., Trivedi, R., Solidification microstructures: a conceptual approach. *Acta Materialia*, 54, 2006, 4289–4303.
- [8] Lan, C.W., et al. Thermocapillary-driven transport in directional solidification melts. *Journal of Crystal Growth*, 498, 2018, 320–329.
- [9] Lappa, M. Thermal convection and free surfaces in microgravity. *Advances in Space Research*, 63, 2019, 2394–2411.
- [10] Liu, S., Trivedi, R., Interface curvature Wang, Hui, Yufang Wang, Xuewei Cao, Lei effects in directional solidification. *Journal of Crystal Growth*, 312, 2010, 2786–2794.
- [11] Ma, D., et al. Interface morphology and stability in directional solidification. *Journal of Crystal Growth*, 582, 2022, 126541.
- [12] Monti, R., et al., Fluid physics experiments in space: relevance to crystal growth. *Advances in Space Research*, 58, (2016) 2030–2046.
- [13] Nepomnyashchy, A., Simanovskii, I. Stability of thermocapillary flows with free surfaces. *Physics of Fluids*, 19, (2007) 072101
- [14] Nguyen-Thi, H., et al., 2012. In situ observation of solidification under microgravity. *Acta Materialia*, 60, 3342–3356.
- [15] Shevtsova, V., Legros, J.C. Thermocapillary convection in crystal growth melts. *Journal of Crystal Growth*, 248, (2003) 555–570.
- [16] Shevtsova, V., Nepomnyashchy, A. Thermocapillary instabilities: recent progress. *Microgravity Science and Technology*, 32, (2020) 741–753.
- [17] Simanovskii, I., Nepomnyashchy, A. Capillary stabilization of free-surface flows. *Physics of Fluids*, 25, (2013) 082101.
- [18] Snoeijer, J.H., Andreotti, B. Moving contact lines: scales and regimes. *Annual Review of Fluid Mechanics*, 45, (2013) 269–292.
- [19] Sun, Z., et al., Thermocapillary effects on free-surface solidification systems. *International Journal of Heat and Mass Transfer*, 215, (2024) 124396.
- [20] Wilcox, W.R., Effects of gravity on crystal growth. *Progress in Crystal Growth and Characterization of Materials*, 48, (2004) 1–24.
- [21] Zhang, N., Wilcox, W.R. Interface stability under weak gravity conditions. *Journal of Crystal Growth*, 552, (2021) 125927.
- [22] Zhang, J., et al. Free-surface effects on interface stability during solidification. *Physics of Fluids*, 32, (2020) 064101.
- [23] Zeng, X., et al. Suppression of flow instabilities by surface tension. *International Journal of Heat and Mass Transfer*, 76, 2014, 505–514.
- [24] Zimmermann, G., et al., Solidification experiments on the International Space Station. *Acta Materialia*, 93, 2015, 52–62.
- [25] Gadkari, D. B., Lal, K. B., Arora, B. M. A Growth of high mobility InSb crystals. (Rapid Communication) *J. Crys Growth*, 175, 1997, 585
- [26] Gadkari, D. B., Lal, K. B., Arora, B. M., 2004. A process for preparation and orientation growth of

single self-seeded crystals of antimonide alloys and/or elementary binary or ternary semiconductors. *Indian Patent, (Filed:139/BOM/1999), Granted No. 192132 (2004),*

[27] Gadkari, D. B., Arora, B. M. Detached Solidification Influences the Crystalline Quality of GaSb Crystals Grown by Vertical Directional Solidification Technique on Earth. *Transac. Mater Soc Japan* 34, (2009), 571

[28] Gadkari, D. B. Advances of the Vertical Directional Solidification Technique for Growth of High Quality InSb Bulk Crystals. *J. Chem. Chem. Eng* 6, 2012, 250

[29] Gadkari, D. B. Advances of the Vertical Directional Solidification Technique for the Growth of High Quality GaSb Bulk Crystal.: *J. Chem. Chem. Eng.* 6, 2012, 65

[30] Gadkari Dattatray, Detached Phenomenon and Its Effect on the Thallium Composition into InSb Bulk Crystal Grown by VDS Technique. *J. Materi. Sci. Eng. A* 2 (9), 2012, 593

[31] Gadkari, D. B., Detached phenomenon: Its influence on the crystal's quality of InSb:Te grown by the VDS technique. *AIP Conf. Proc.* 1512, 2013, 856.

<http://dx.doi.org/10.1063/1.4791308>

[32] Gadkari, Dattatray, Detached Crystal Growth in VDS Technique: A New Crystal Growth Process. *J. Materials Science and Engineering A* 3 (5), 2013, 338

[33] Gadkari Dattatray, 2013. Detached phenomenon: Its effect on the crystal quality of Ga (1- x) InxSb bulk crystal grown by the VDS technique. *Materials Chemistry and Physics* 139, 2014, 375, <https://doi.org/10.1016/j.matchemphys.2012.09.060>

[34] Gadkari, D. B., Detached Growth: Unfolding Four Decades Growth Mystery into Vertical Directional solidification Technique on Earth. *In. J. Scien. Resea. Public.* 4, 2013. 15

[34] Gadkari Dattatray, Doped InSb Detached Crystals by VDS Technique: Its Substrates for Infrared Devices and Physics Concept. *In. J. Engin. Applied Sciences (IJEAS)* 2, 2015, 39

[36] Gadkari, D., Maske, D., Deshpande, M., Arora B. M. Detached/Contactless Growths, Reduced Melt Convection and Its Effect on the Device Grade Substrates of Sb-Based Crystals Grown by VDS on Earth. *In. J. Innov. Research in Sci. Engin. Techno.* 5, 2016. [doi:10.15680/IJRSET.2016.0502059](https://doi.org/10.15680/IJRSET.2016.0502059)

[37] Gadkari, D. B. The detached phenomenon and the fundamental science behind: The novel vertical directional solidification growth of the detached crystals by slow freezing. *Int. J. Engin. Rese. Appli.* 9, 2019, 1

[38] Gadkari, D. B., The homogeneous and entire detached In_{0.5}Ga_{0.5}Sb alloy crystals grown by the slow freezing using novel VDS-process. *In. J. Engin. Res. Appli.* 10(5), 2020, 7

[39] Gadkari, D. B., 2020. Investigation of influence of the indium doping on the properties of the Ga(1-x)InxSb (x=0.10, 0.15, 0.25) crystals: Detached growth by the VDS-process. *In. J. Engin. Res. Appli.* 2020, 10(9), 5

[40] Gadkari, D. B. Study of the Ga doped In(1-x)GaxSb (x= 0.10, 0.15, 0.25) crystals the compositional, structural, electrical, and the microstructures properties: Growth by the VDS-process. *In. J. Engin. Res. Appli.* 10(10), 2020, 35

[41] Gadkari, Dattatray B., Evaluation of the thermodiffusion impact across two phases of the alloys and the crystal-melt interface in In_{0.5}Ga_{0.5}Sb un-seeded crystallization growth by the VDS process. *Intern J Engin Res Appli.* 11, 2025, 121-132

[42] Gadkari Dattatray. Experimental Investigation of Entirely Detached Growth in Vertical Directional solidification and Crystallization Evolution. *International Journal of Science and Technology*, 17, 2026., 1. DOI: <http://doi.org/10.71097/IJSAT.v17.it.10166>