ROLE OF FLUID TRANSPORT ON SEALING EFFECTIVENESS OF AIR CURTAINS

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Submitted

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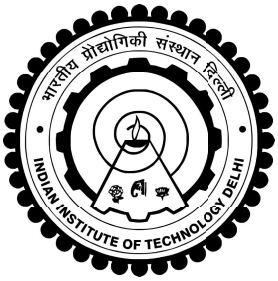

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Certificate

This is to certify that the thesis entitled "**Role of fluid transport on sealing effectiveness of air curtains**", submitted by **Mr. Tanmay Agrawal** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** is a record of the original, bona fide research work carried out by him under our supervision. The thesis works meets the requisite standards and the candidate is worthy of consideration for the degree of Doctor of Philosophy in accordance with the regulations of the institute.

The results contained in this thesis have not been submitted in part or in full to any other university or institute for the award of any degree or diploma.

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for the analysis presented in this thesis. Throughout my candidature, several other students in the department were involved in flow simulations and offered their insights. Most notably, discussions with Diptanu Das, who studied buoyant air curtains using RANS for his MSR thesis, advanced my physical understanding of the buoyancy effects in an ACD.

Towards data processing and developing a deeper understanding of buoyancy-driven turbulent flows, I have had fruitful discussions with colleagues, both past and present, who deserve special mention. Dr. Siva Heramb Peddada (Siva Garu) and Dr. Nitin Kumar (Badka Ji) have been invaluable in conducting simulations, analyzing results, and interpreting computational data. I have also greatly benefited from discussions with my former colleagues, Dr. Rahul Deshpande and Dr. Tushar Sikroria, who, at various times, have nudged me in the right direction. Rahul's timely advice on data analysis, along with Tushar's insights on PIV, saved me a great deal of time I would have otherwise spent searching through the internet. I would also thank Dr. Bhaarath Ramesh, with whom I have had many technical and non-technical telephonic conversations, which filled me with a sense of joy and calmness.

While it is generally conceived that a PhD journey is highly academic (which it is), it need not be monotonous. I have been fortunate to avoid that aspect thanks to a wonderful group of friends with whom I have shared countless moments over great food and drinks. Not surprisingly, many of them are my lab mates, with whom my collaboration extended far beyond academics. In no particular order, I had the company of Arnab, Niladri, Sitaram, Suraj, Vamsi, Bhramar, Manoj, Divyaprakash, Srihari, Datti, Amrat, Shoaib, Prantik, Shivam, Varnit, Subrat, Deepshikha, Pratyush, and Amar over food, cricket, badminton, and outings. During my time at Kumaon Hostel, the memories created with Drs. Shubham Dubey, Krishna Gola, and Ashutosh Negi, and juniors including Aman, Jatin, Rohit, Harsh, Prayag, Rishabh, Himanshu, Dharamjeet, and Milind will always be cher-

ished for years to come. Away from home, I had the kind acceptance of my colleague Shishir bhaiya (Dr. Sahab) and his family, who were always there to provide hearty meals whether I was healthy or sick, and to offer support and encouragement throughout my academic progress. I look forward to Swastik's (their child's) wonderful future.

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ABSTRACT

Fluid flow across openings in buildings arises due to buoyancy forces caused by indoor-outdoor temperature differences, wind effects, and pressure gradients. These flows often lead to undesirable transport of heat, mass, contaminants, and pollutants, posing a challenge to maintaining energy-efficient, clean, and comfortable indoor environments. Heating Ventilation and Air-Conditioning (HVAC) systems are therefore forced to work harder to compensate for this unregulated exchange, resulting in increased energy consumption. One effective mitigation strategy is the use of air curtain devices (ACDs) installed on doorways, which generate a high-momentum jet that acts as an aerodynamic separation barrier and suppress the buoyancy-driven exchange while allowing uninterrupted passage through them. ACDs have been deployed in various configurations, including vertical, horizontal, twin-jet, and recirculating designs, depending on functional needs. Their performance depends on the balance between jet momentum flux and opposing buoyancy forces, captured by a non-dimensional parameter called the deflection modulus, D_m. For an optimally designed ACD, the jet inhibits gravity currents which are horizontal intrusions of buoyant fluid driven by the density difference. However, if the jet momentum is insufficient, the curtain becomes unstable, reducing its sealing effectiveness.

The present study aims to provide a deeper understanding of the flow physics governing a vertically blowing air curtain. The primary objective is to investigate the interaction between the plane jet and the opposing gravity current, examining how their interplay

affects the stability, dynamics, and overall effectiveness of the curtain. The influence of buoyancy is analyzed through comparisons with non-buoyant jets and turbulent fountains. We also assess the impact of assistive buoyancy, which is introduced by using a denser curtain fluid, on suppressing fluid infiltration. Finally, the study investigates the transport pathways through which outdoor fluid enters the indoor space, even when an air curtain is in place. These insights aim to explain the mechanisms that limit sealing performance and identify the operating conditions under which aerodynamic sealing can approach its ideal behavior.

The present study employs a combination of computational and experimental methods to investigate the dynamics of vertically blowing ACDs. Numerically, both Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulation (LES) approaches are used to obtain spatiotemporal distributions of velocity and density fields, with LES performed using the high-fidelity in-house solver SOMAR for enhanced accuracy. Experimentally, time-resolved particle image velocimetry (PIV) is conducted in a refractive index-matched setup to capture temporal velocity fields. These measurements are complemented by planar flow visualizations using dye injection for qualitative assessment, and by bulk density and conductivity measurements before and after each trial to accurately quantify sealing effectiveness. Additionally, a reduced-order analytical model is developed to predict jet deflection and velocity characteristics, which are compared with the numerical data. Together, these methods offer a synergetic approach to thoroughly investigate the factors governing air curtain performance and the associated fluid transport mechanisms.

The results from this study provide a detailed analysis of air curtain behavior across various operating conditions, highlighting the critical role of deflection modulus, D_m, in determining flow stability and sealing performance. For neutrally buoyant air curtains (NBACs),

where curtain density matches the indoor environment, experimental observations and LES results confirm that the sealing effectiveness, E, is significantly low for unstable ACDs ($D_m \lessapprox 0.1$) and achieves a maximum value in the vicinity of $D_m \approx 0.2$ when the curtain becomes stable. LES predictions show strong agreement with experimental values, unlike RANS, which under-predicts effectiveness due to its inherent averaging. When assisting buoyancy is introduced using denser curtain fluids, termed heavy air curtains (HACs), infiltration of outdoor fluid reduces by nearly 25% at moderate values of D_m. Dynamically similar laboratory experiments, employing sugar solution as curtain fluid and salt- and freshwater as outdoor and indoor analogs, confirm that assistive buoyancy improves performance, achieving sealing effectiveness up to 0.85. The transport mechanisms associated with the fluid which contributes to this 15% exchange and infiltrates into the indoor region through the air curtain is still not very well understood. To address this, the present study adopts a Lagrangian particle tracking method which examines the trajectories of fluid particles that migrate from the outdoor region to the indoor space. Results indicate that even under the established conditions when an ACD completely inhibits the gravity current, fluid particles are entrained into the air curtain jet and subsequently penetrate the indoor environment after impingement on the floor.

The statistical characteristics of air curtains is examined through direct comparison with non-buoyant plane jets and turbulent fountains. At moderate values of D_m, air curtains exhibit significant inclination from the vertical, resulting in distinct temporal flow evolution in indoor and outdoor regions due to buoyancy effects. Ensemble-averaged data from PIV measurements and high-fidelity LES computations reveal that ACDs exhibit asymmetric lateral spreading, particularly toward the buoyant (outdoor) side, as a consequence of jet interaction with lateral density stratification. This asymmetry is also evident in the tur-

bulence statistics, leading to deviations from the self-similar behavior typically observed in plane turbulent jets. Laboratory measurements and numerical data coherently suggests that the decay rate of centreline velocity (K_W), and the spreading rate of halfwidth (K_δ) of air curtains are higher as compared to non-buoyant jets. For fountains developing in a uniform ambient, K_W and K_δ are found to be negatively correlated with the source Froude number, Fr_0. Furthermore, integral estimations of volume and momentum fluxes reveal that entrainment coefficients for ACDs increase by up to 20%, compared to configurations without lateral density differences. Whereas for the high-Fr_0 fountains, the fluid entrainment is similar to a non-buoyant jet.

In conclusion, this thesis presents a comprehensive analysis of air curtain dynamics under realistic buoyancy influences, integrating experimental observations with high-fidelity simulations to evaluate sealing effectiveness and characterize fluid transport. Novel insights into the general structure of air curtains and turbulent line fountains, including their velocity statistics and entrainment characteristics, are presented. To further advance this work, future studies could investigate the time-resolved evolution of instantaneous fluid transport across the turbulent/non-turbulent interface (TNTI), as well as the development of fluid instabilities on either side of the air curtain jet arising from the interaction of fluids with differing densities.

सार

भवनों में खुले स्थानों के आर-पार द्रव प्रवाह मुख्यतः इनडोर और आउटडोर तापमान में अंतर, वायु प्रभावों और दाब प्रवणताओं के कारण उत्पन्न उर्ध्वगामी बलों से होता है। ये प्रवाह प्रायः ऊष्मा, द्रव्य, प्रदूषक तथा अन्य हानिकारक तत्वों के अवांछनीय आदान-प्रदान का कारण बनते हैं, जिससे ऊर्जा-कुशल, स्वच्छ और आरामदायक इनडोर वातावरण बनाए रखना चुनौतीपूर्ण हो जाता है। इसके परिणामस्वरूप ताप, वेंटिलेशन और वातानुकूलन प्रणालियों को अधिक परिश्रम करना पड़ता है, जिससे ऊर्जा की खपत बढ़ जाती है। एक प्रभावी समाधान दरवाजों पर वायु परदों का उपयोग है, जो उच्च वेग का एक जेट प्रवाह उत्पन्न करते हैं और एक वायुगतिकीय अवरोधक के रूप में कार्य करते हुए उर्ध्वगामी प्रवाहों को रोकते हैं, साथ ही निर्बाध आवागमन की अनुमति भी देते हैं। वायु परदों को कार्यात्मक आवश्यकताओं के अनुसार लंबवत, क्षैतिज, द्वि-जेट तथा पुनर्चक्रित डिज़ाइन में स्थापित किया जाता है। इनकी कार्यक्षमता जेट के वेगीय बल और विपरीत उर्ध्वगामी बलों के बीच संतुलन पर निर्भर करती है, जिसे एक अदिमांक मानक द्वारा व्यक्त किया जाता है। यदि वायु पर्दा उपयुक्त रूप से डिज़ाइन किया गया हो, तो जेट प्रवाह गुरुत्वीय धाराओं, अर्थात घनत्व भिन्नता से प्रेरित क्षैतिज प्रवाहों, को रोक देता है। परन्तु यदि जेट का वेग बल अपर्याप्त हो, तो पर्दा अस्थिर हो जाता है और उसकी प्रभावशीलता घट जाती है।

यह अध्ययन एक लंबवत प्रवाहित वायु पर्दे के प्रवाहीय भौतिकी को गहराई से समझने के उद्देश्य से किया गया है। इसका मुख्य उद्देश्य समतल जेट प्रवाह और विपरीत दिशा में प्रवाहित गुरुत्वीय धारा के बीच अंतःक्रिया का परीक्षण करना है तथा यह विश्लेषण करना है कि इनका आपसी प्रभाव पर्दे की स्थिरता, गतिकी और समग्र प्रभावशीलता को किस प्रकार प्रभावित करता है। अध्ययन में गैर-उर्ध्वगामी जेट प्रवाह तथा अशांत जलप्रपातों के साथ तुलना करके उर्ध्वगामी बलों के प्रभावों का भी विश्लेषण किया गया है। साथ ही, पर्दे के तरल के घनत्व को बढ़ाकर सहायक उर्ध्वगामी बल उत्पन्न करने के प्रभाव का परीक्षण किया गया है, जो बाहरी द्रव के प्रवेश को कम करने में सहायक होता है। अंत में, यह अध्ययन उन मार्गों का अन्वेषण करता है जिनसे बाहरी द्रव वायु पर्दे की उपस्थिति के बावजूद इनडोर क्षेत्र में प्रवेश करता है। यह समझ वास्तविक प्रवाह तंत्रों को स्पष्ट करने में सहायता करेगी जो पर्दे की सीलिंग प्रभावशीलता को सीमित करते हैं, तथा उन परिस्थितियों की पहचान करेगी जिनमें वायुगतिकीय सीलिंग आदर्श प्रदर्शन के निकट पहुँच सकती है।

यह अध्ययन वायु परदे की गतिकी के विश्लेषण हेतु संगणकीय तथा प्रायोगिक दोनों विधियों का उपयोग करता है। संगणकीय रूप से, पुनरावृत्त औसत नवियर-स्टोक्स समीकरणों और बड़े भंवर सिमुलेशन विधियों द्वारा वेग तथा घनत्व क्षेत्रों के स्थानिक-कालिक वितरण प्राप्त किए गए हैं। बड़े भंवर सिमुलेशन के लिए उच्च गुणवत्ता वाले आंतरिक सॉफ्टवेयर का प्रयोग किया गया है। प्रायोगिक रूप में, समय-संवेदनशील कण चित्र वेगमिति तकनीक द्वारा एक समान अपवर्तनांक वाले सेटअप में प्रवाह क्षेत्र का मापन किया गया है। इन मापों को रंग घोल प्रविष्टि द्वारा प्रवाह का दृश्यांकन कर और प्रत्येक परीक्षण से पहले तथा बाद में घनत्व और चालकता मापकर सत्यापित किया गया है। इसके अतिरिक्त, जेट विक्षेपण और वेग विशेषताओं की भविष्यवाणी हेतु एक सरल गणितीय मॉडल विकसित किया गया है, जिसकी तुलना संगणकीय परिणामों से की गई है। ये सभी विधियाँ मिलकर वायु पर्दे के प्रदर्शन तथा संबंधित द्रव परिवहन तंत्रों की व्यापक जांच प्रस्तुत करती हैं।

अध्ययन के परिणाम विभिन्न परिचालन स्थितियों में वायु परदे के व्यवहार का विस्तृत विश्लेषण प्रदान करते हैं और दिखाते हैं कि विचलन गुणांक वायु पर्दे की स्थिरता और सीमांकन क्षमता में महत्वपूर्ण भूमिका निभाता है। तटस्थ घनत्व वाले वायु पर्दों के लिए, जहाँ पर्दे का द्रव इनडोर वातावरण के घनत्व के समान होता है, प्रायोगिक अवलोकन और बड़े भंवर सिमुलेशन से यह पुष्टि हुई है कि जब विचलन गुणांक लगभग 0.1 से कम होता है तब पर्दा अस्थिर होता है और सीमांकन क्षमता बहुत कम रहती है, जबकि विचलन गुणांक लगभग 0.2 के आसपास पहुँचने पर पर्दा स्थिर हो जाता है और अधिकतम सीमांकन क्षमता प्राप्त होती है। बड़े भंवर सिमुलेशन के परिणाम प्रायोगिक मापनों से अच्छी तरह मेल खाते हैं, जबकि पुनरावृत्त औसत नवियर-स्टोक्स सिमुलेशन सीमांकन क्षमता को कम आंकते हैं। जब भारी वायु पर्दे का उपयोग किया गया, अर्थात घनत्व बढ़ाकर सहायक उर्ध्वगामी बल डाला गया, तो लगभग 25 प्रतिशत तक बाहरी द्रव का प्रवेश कम हुआ। प्रयोगशाला प्रयोगों में चीनी घोल को पर्दे के द्रव के रूप में और नमक तथा ताजे पानी को बाहरी और इनडोर द्रव के अनुरूप उपयोग किया गया, और पाया गया कि सहायक उर्ध्वगामी बल से सीमांकन क्षमता 0.85 तक पहुँच सकती है।

हालाँकि, अभी भी लगभग 15 प्रतिशत बाहरी द्रव इनडोर क्षेत्र में प्रवेश करता है, जिसकी प्रवाह प्रक्रिया पूरी तरह से नहीं समझी गई थी। इस समस्या को हल करने के लिए, अध्ययन में लैग्रेंजियन कण ट्रैकिंग तकनीक अपनाई गई, जिसमें उन तरल कणों की यात्रा का अध्ययन किया गया जो बाहरी क्षेत्र से इनडोर क्षेत्र में प्रवेश करते हैं। परिणाम बताते हैं कि जब वायु पर्दा गुरुत्वीय धारा को पूरी तरह रोकता है, तब भी कुछ तरल कण वायु पर्दे के जेट में सम्मिलित

होकर फर्श से टकराने के बाद इनडोर क्षेत्र में प्रवेश कर जाते हैं।

वायु पर्दों के सांख्यिकीय व्यवहार का विश्लेषण गैर-उर्ध्वगामी समतल जेट प्रवाहों और अशांत जलप्रपातों के साथ प्रत्यक्ष तुलना करके किया गया। मध्यम विचलन गुणांक मानों पर वायु परदे में ऊर्ध्वाधर दिशा से पर्याप्त झुकाव देखा गया, जिससे इनडोर और बाहरी क्षेत्रों में प्रवाह की समय के साथ अलग-अलग विकास प्रक्रिया देखी गई। समष्टि औसत आंकड़ों से पता चलता है कि वायु परदे पार्श्व दिशा में विषम प्रसार करते हैं, विशेषतः उर्ध्वगामी (बाहरी) दिशा में, जो पार्श्व घनत्व संरचनाओं के कारण उत्पन्न होता है। यह विषमता प्रवाह में अशांतता के आंकड़ों में भी प्रकट होती है, जिसके कारण वायु परदे पारंपरिक समतल अशांत जेटों में देखी जाने वाली समानता का पालन नहीं करते। प्रयोगशाला मापन और संगणकीय आंकड़े यह भी दर्शाते हैं कि वायु परदे की केंद्ररेखीय वेग क्षय दर और अर्ध-चौड़ाई फैलाव दर गैर-उर्ध्वगामी जेट प्रवाहों की तुलना में अधिक होती है। एकसमान परिवेश में विकसित जलप्रपातों के लिए यह दरें स्रोत उर्ध्वगामी बलांक के साथ नकारात्मक रूप से संबंधित पाई गईं। इसके अलावा, संवेग और आयतन प्रवाह के समाकलन से पता चलता है कि वायु पर्दों के अंतर्वेशन गुणांक में लगभग 20 प्रतिशत तक वृद्धि होती है, जबकि उच्च स्रोत उर्ध्वगामी बलांक वाले जलप्रपातों में यह अंतर्वेशन गैर-उर्ध्वगामी जेट के समान रहता है।

अंततः, यह शोध वास्तविक उर्ध्वगामी प्रभावों के अधीन वायु पर्दे की गतिकी का एक समग्र विश्लेषण प्रस्तुत करता है, जो प्रायोगिक टिप्पणियों और उच्च गुणवत्ता वाले संगणकीय सिमुलेशन के समन्वय से सीमांकन क्षमता और द्रव प्रवाह की प्रकृति का मूल्यांकन करता है। वायु परदे और अशांत रेखीय जलप्रपातों की संरचना, वेग सांख्यिकी और अंतर्वेशन विशेषताओं में नवीन अंतर्दृष्टियाँ प्रस्तुत की गई हैं। भविष्य में, तात्कालिक द्रव प्रवाह के समय के साथ विकास और विभिन्न घनत्वों वाले द्रवों के बीच उत्पन्न प्रवाहीय अस्थिरताओं के अध्ययन द्वारा इस कार्य को और आगे बढ़ाया जा सकता है।

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ρ_0	Density of the air curtain fluid
ρ_l	Density of the light fluid
ρ_d	Density of the dense fluid
b_0	Exit thickness of the air curtain
w_0	Exit velocity of the air curtain
g	Acceleration due to gravity
H	Doorway height
D_m	Deflection modulus
E	Sealing effectiveness
g'	Reduced gravity
$\mathbf{u}$	Instantaneous velocity vector
$\overline{\mathbf{u}}$	Mean velocity vector
$\mathbf{u}'$	Fluctuating velocity vector
p	Instantaneous fluid pressure
$\overline{p}$	Mean fluid pressure
p'	Fluctuating fluid pressure
T	Fluid temperature
$\mathbf{x}$	Coordinate vector
t	Time
t^*	Dimensionless time
ν	Kinematic viscosity
κ	Thermal diffusivity
k	Turbulent kinetic energy
ϵ	Dissipation rate of k

τ_{ij}^{R}	Subgrid stress tensor
λ^{R}	Subgrid buoyancy flux
Re	Reynolds number
Fr	Froude number
V_r	Velocity ratio
S	Density difference ratio for heavy curtains
$x_{_{sb}}$	Lateral spread on the buoyant side
$x_{_{snb}}$	Lateral spread on the non-buoyant side
$\overline{\theta}$	Mean inclination of the air curtain
$w_{_{\xi}}$	Streamwise velocity component
$u_{_{\eta}}$	Streamnormal velocity component
$K_{_{W}}$	Decay rate of centreline velocity
$\delta_{_{0.5}}$	Jet halfwidth
$K_{_{\delta}}$	Spread rate of jet halfwidth
Q	Volume flux
M	Momentum flux
$\alpha_{_{I}}$	Integral entrainment coefficient
X_f	Particle crossing fraction
n_p^0	Initial number of seeding particles
$\tau(t)$	Tortuosity of the particle trajectory

List of abbreviations

HVAC	Heating, ventilation and air-conditioning
ACD	Air curtain device
RANS	Reynolds-averaged Navier-Stokes
LES	Large-eddy simulation
SOMAR	Stratified ocean model with adaptive refinement
PIV	Particle image velocimetry
NBAC	Neutrally buoyant air curtains
HAC	Heavy air curtains
TNTI	Turbulent/non-turbulent interface
IAQ	Indoor air quality
CFD	Computational fluid dynamics
LDA	Laser doppler anemometry
FDM	Finite difference method
RDC	Refrigerated display cabinets
ELF	External lateral flow
RNG	Renormalization group
RMS	Root mean square
CFL	Courant-Friedrichs-Lewy
LG	Lock gate
ST	Supply tank
DIT	Dye injection tank
LEF	Lock-exchange flow
GCI	Grid convergence index
HWA	Hot wire anemometry

KH	Kelvin-Helmholtz
TKE	Turbulent kinetic energy
NBJ	Non-buoyant jet
PIF	Plane impinging fountain
ODE	Ordinary differential equation
GC	Gravity current
ED	Entrainment-detrainment
EI	Entrainment-impingement
PLIF	Planar laser-induced fluorescence