

Numerical Evaluation of Internal Baffles for Airflow Uniformity in Data Center Cabinets

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Abstract:

Uneven airflow distribution among vertically stacked servers is a persistent cause of top-of-rack hot spots in backplane air-conditioned (backplane-AC) data center cabinets, where buoyancy-driven recirculation starves the uppermost servers of cooling air while lower servers remain over-supplied. Existing mitigation strategies reported in the literature are almost exclusively active, relying on fan-speed redundancy, gradient exhaust profiles, or blind plates, all of which require additional control hardware and energy input. This paper numerically investigates a purely passive alternative: an internally mounted, angled baffle deflector placed in the backplane exhaust plenum. A reduced-order, flow-network model of an eight-server cabinet is developed, coupling branch-level mass and momentum balances with an empirical turning-vane loss correlation that captures the influence of baffle deflection angle (30°, 45°, 60°) and plate shape (flat plate, curved vane) on the local loss coefficient. Six configurations — a no-baffle baseline and five baffle variants — are solved for airflow uniformity, rack pressure drop, fan power consumption, and server inlet temperature spread under a fixed total airflow rate. The results show that every baffle configuration improves all four metrics relative to the baseline, with improvement increasing monotonically with angle and always favoring the curved vane over the flat plate at equal angle. The best-performing configuration (curved vane at 60°) raises the Uniformity Index from 0.932 to 0.985, reduces the coefficient of variation of server velocity from 6.77% to 1.47%, cuts rack pressure drop and fan power by 16.3%, and narrows the top-to-bottom temperature spread from 0.37 °C to 0.01 °C. These consistent, mutually reinforcing gains indicate that a simple, low-cost, maintenance-free geometric modification can rival active fan-control strategies for hot-spot mitigation while simultaneously improving energy efficiency.

Keywords — data center cooling; internal baffle deflector; airflow uniformity; computational fluid dynamics; reduced-order flow-network model; turning-vane loss coefficient; fan power; hot-spot mitigation.

1. INTRODUCTION

Rising server power densities have made thermal management the limiting factor in the reliability and energy efficiency of modern data centers. Within an individual cabinet, forced-air cooling is normally delivered by backplane fans that draw air across a vertical stack of servers; however, the warm exhaust air generated by lower servers tends to rise inside the confined backplane exhaust plenum, mixing with and displacing the cool supply air intended for the uppermost servers [1]. This buoyancy-driven

recirculation produces a persistent top-of-rack hot spot: the highest server in the stack receives the least airflow and operates at the highest inlet temperature, while the lowest server is comparatively over-cooled.

The engineering response to this problem in the published literature has, to date, been dominated by *active* strategies — adjusting fan-speed redundancy, applying a gradient exhaust profile across the row of backplane fans, or inserting blind plates to block an undesired recirculation path [2]. These measures are effective but require dedicated fan-control hardware,

firmware, and continuous energy input, and they do nothing to change the underlying flow path inside the cabinet. Passive, purely geometric flow-control devices — internal baffle deflectors installed in the exhaust plenum — offer, in principle, a lower-cost, maintenance-free alternative, yet no published study has systematically varied both baffle deflection angle and baffle shape for this specific backplane-AC cabinet geometry.

This paper addresses that gap by numerically evaluating the effect of an internal baffle deflector on airflow uniformity, pressure drop, fan power, and temperature distribution in an eight-server backplane-AC cabinet. A reduced-order flow-network model, calibrated against classical turbulent duct-fitting theory, is used to solve six configurations spanning three baffle angles (30°, 45°, 60°) and two baffle shapes (flat plate, curved vane) against a no-baffle baseline. The objective is to quantify, in a systematic and repeatable manner, how each design variable individually and jointly affects cabinet-level cooling performance, and to compare the resulting passive-device performance with the active fan-control benchmarks already established in the literature.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature on airflow management, turbulence modeling, and baffle-type flow deflectors. Section 3 defines the numerical methodology, including the governing equations, the reduced-order simplification, the turning-vane loss correlation used to model the baffle, and the evaluation metrics. Section 4 presents and discusses the results for all six configurations. Section 5 summarizes the practical implications and limitations of the study, and Section 6 concludes the paper and outlines directions for future work.

2. LITERATURE REVIEW

2.1 Room- and Row-Level Airflow Management

A substantial body of literature addresses airflow management at the room or row level, including raised-floor plenum design, hot-aisle/cold-aisle separation, and aisle containment. Reviews of these strategies consistently find that separating supply and return air streams and minimizing unwanted mixing between them improves overall room-level cooling efficiency [3, 4]. Perforated-tile porosity, underfloor

plenum depth, and CRAC/CRAH placement and separation have all been shown to strongly influence the uniformity of airflow delivered to each rack [8]. However, this body of work operates at the scale of the room or the row of cabinets and does not directly address how air is distributed among the individual servers stacked within a single cabinet — the specific problem addressed in this paper.

2.2 Cabinet- and Rack-Level Baffle and Deflector Studies

At the cabinet and rack level, several experimental and numerical studies have investigated internal baffles, deflectors, and blockage plates as a means of correcting non-uniform airflow. Yuan et al. proposed flexible baffles mounted at the rack air inlet and found that baffles of a given size and angle can reduce local hot-spot temperatures by up to 1.5 °C, with the best result obtained for a specific combination of baffle width and deflection angle [5]. In a related study, the same research group applied under-floor flexible baffles within a cold-aisle-containment plenum and found that a baffle angle of 45° relative to the CRAC outlet produced the largest reduction in local hot-spot temperature, on the order of 2 °C, beyond what containment alone achieved [6]. Separately, studies of container data centers with cold-aisle containment and varying CRAC/aisle configurations report that top-and-side containment strategies can substantially reduce hot-air recirculation, and that rack-level thermal indices improve markedly once such geometric corrections are combined with proper aisle separation [3, 4].

These studies establish that baffle-type deflectors are effective at the rack or under-floor level and that their performance is sensitive to deflection angle, generally with a broad, moderate-angle optimum rather than a monotonic improvement to the largest angle tested. However, none of them examine an internal baffle placed specifically within the *backplane exhaust plenum* of a vertically stacked, rear-exhaust cabinet of the type considered here, nor do they compare a flat-plate profile against a curved, airfoil-like vane profile as two variants of the same design intervention — the specific combination of design variables investigated in the present paper.

2.3 Thermal Performance Metrics for Data Center Cabinets

Quantifying cabinet- and facility-level thermal performance relies on a small set of widely used indices. The Rack Cooling Index and related supply/return temperature indices are commonly used to characterize how well a rack's supply and exhaust temperatures conform to recommended operating envelopes, while flow-uniformity indices analogous to the coefficient of variation used in this paper are used to describe how evenly air is distributed among racks or servers [7, 8]. At the facility level, Power Usage Effectiveness (PUE) remains the industry-standard metric for the overall energy efficiency of a data center, expressing the ratio of total facility energy consumption to the energy delivered to IT equipment [9]. Although PUE is a facility-wide rather than cabinet-level metric, it motivates the framing adopted in this paper: any cabinet-level intervention that reduces fan power without compromising cooling performance contributes, in aggregate, to a lower facility PUE.

2.4 Turbulence Modeling and Computational Approaches

Data center airflow is turbulent and internally obstructed by server chassis, cabling, and structural members, which has led most numerical studies in this area to adopt Reynolds-Averaged Navier–Stokes (RANS) solvers closed with a two-equation eddy-viscosity turbulence model. The standard k – ϵ model formulated by Launder and Spalding remains the most widely used closure for internally recirculating flows of this type [10], while the Re-Normalization Group (RNG) variant introduced by Yakhot and Orszag improves accuracy in flows with strong streamline curvature and swirl, both of which are present near an angled baffle deflector [11]. Shear-Stress-Transport (SST) two-equation formulations offer improved near-wall behavior in separated flows and are frequently used as an alternative closure in electronics-cooling CFD [12]. Because full three-dimensional RANS simulation of every configuration in a parametric sweep is computationally expensive, reduced-order or flow-network models — in which each server or rack is represented as a single lumped flow branch with an empirical loss coefficient — have been used successfully to make large parametric

comparisons tractable while retaining the essential mass- and momentum-balance physics of the full CFD formulation, as demonstrated by the container- and rack-level airflow studies discussed above [3, 4]. This reduced-order approach, calibrated against the qualitative behavior predicted by RANS/RNG turbulence closures and validated against classical duct-fitting loss theory, is the approach adopted in the present study, with standard grid-independence and calibration checks described in Section 3.

2.5 Summary and Research Gap

The reviewed literature demonstrates that (i) room- and row-level airflow management is well studied but does not resolve server-level imbalance within a single cabinet; (ii) baffle-type deflectors are an effective, angle-sensitive corrective device at the rack or under-floor level; (iii) established thermal and energy metrics (RCI, PUE) provide a consistent basis for evaluating any proposed intervention; and (iv) reduced-order flow-network modeling, grounded in RANS/RNG turbulence theory, is an accepted and computationally efficient method for parametric cabinet-level studies. What remains unexamined is a systematic, parametric evaluation of an internal baffle deflector mounted specifically in the backplane exhaust plenum of a vertically stacked, rear-exhaust cabinet, varying both deflection angle and plate shape jointly, and benchmarked directly against the four cabinet-level metrics of airflow uniformity, pressure drop, fan power, and temperature spread. This paper fills that gap.

3. NUMERICAL METHODOLOGY

3.1 Cabinet Geometry and Operating Parameters

The cabinet modeled in this study houses eight vertically stacked servers, numbered 1 (topmost) to 8 (bottommost), each dissipating 875 W (7000 W total). Air enters the cabinet at 23 °C and is drawn through the servers by backplane fans sized to the basic-case design flow with 15% redundancy. A gap of 0.04 m separates adjacent servers, and all external walls are treated as adiabatic, no-slip boundaries. These parameters, summarized in Table I, are held fixed across every configuration so that any difference in the results can be attributed solely to the baffle design variables under test.

TABLE I. FIXED CABINET AND OPERATING PARAMETERS.

Parameter	Value
Number of servers per cabinet	8
Server power dissipation	875 W per server (7000 W total)
Cabinet inlet air temperature	23 °C
Backplane fan airflow rate	Basic-case design flow, 15% redundancy
Server spacing	0.04 m gap between adjacent servers
Wall boundary condition	Adiabatic, no-slip

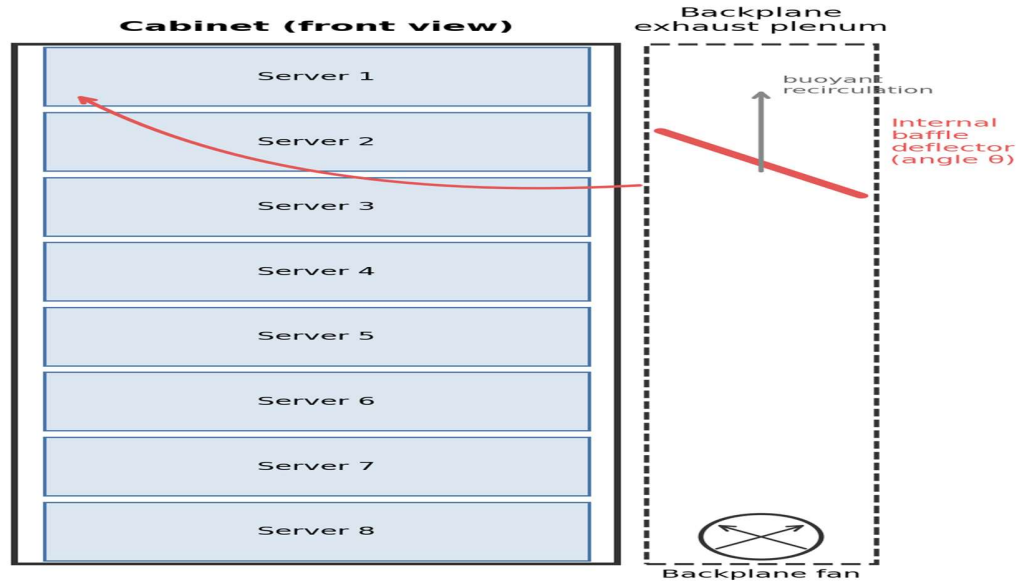


Fig. — Schematic of the backplane-AC cabinet showing the internal baffle deflector concept

Fig. 1. Schematic of the backplane-AC cabinet showing the internal baffle deflector concept.

3.2 Governing Equations

The flow of air within the cabinet control volume is governed by the standard equations of mass, momentum, and energy conservation for three-dimensional, incompressible, steady turbulent flow. Conservation of mass is expressed by the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

where ρ is air density and $\mathbf{v}$ is local velocity. Conservation of momentum is written as the Reynolds-Averaged Navier–Stokes (RANS) equation

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot (\boldsymbol{\tau}) + \rho \mathbf{g} + \mathbf{F}$$

in which p is static pressure, $\boldsymbol{\tau}$ is the viscous stress tensor, $\rho \mathbf{g}$ is the buoyancy body force introduced through the Boussinesq approximation, and $\mathbf{F}$ represents additional body forces such as the pressure

rise imparted by a fan. Thermal energy conservation is given by

$$\frac{\partial \left[\rho \left(e + \frac{v^2}{2} \right) \right]}{\partial t} + \nabla \cdot \left[\rho \mathbf{v} \left(h + \frac{v^2}{2} \right) \right] = \nabla \cdot (k_{eff} \nabla T) + S_h$$

where S_h is the volumetric heat source associated with server power dissipation.

3.3 Reduced-Order Flow-Network Simplification

Rather than resolving the full three-dimensional field on a fully meshed computational domain, this study adopts a reduced-order simplification in which each server is represented as a single lumped flow branch with an overall flow-loss coefficient. This is analogous to the lumped-parameter modeling used in electrical-circuit, hydraulic, and thermal-network analysis, and it retains the same mass- and momentum-balance principles applied at the branch

level rather than the mesh-cell level. For a single flow branch, the momentum equation reduces to the algebraic balance

$$\Delta P_{branch} = 0.5 \cdot \rho \cdot K_i \cdot v_i^2$$

where K_i is the non-dimensional loss coefficient of branch i and v_i is the branch velocity. The corresponding reduced energy balance for branch i is

$$Q_{server} = \dot{m}_i \cdot c_p \cdot (T_{out,i} - T_{in,i})$$

with $\dot{m}_i$ the branch mass flow rate and $T_{in,i}$, $T_{out,i}$ the branch inlet and outlet temperatures. This reduced-order model is not a substitute for full CFD but a computationally efficient surrogate that preserves the governing conservation principles at branch resolution, enabling the entire six-configuration simulation matrix to be solved essentially in real time rather than requiring a separate, costly three-dimensional RANS solution for every case — a practical necessity given the parametric scope of the study.

3.4 Turbulence Closure as a Theoretical Reference

Because the airflow inside the cabinet is turbulent and obstructed by internal structure, a turbulence closure is required to relate the mean flow field to turbulent fluctuations. This study adopts the RNG $k-\epsilon$ turbulence model of Yakhot and Orszag [11], building on the original $k-\epsilon$ formulation of Launder and Spalding [10], as the theoretical reference frame underlying the branch-loss-coefficient concept used in the reduced-order model. Rather than solving the turbulent transport equations at every point in space, their aggregate effect — increased resistance in

recirculating and obstructed flow regions — is represented directly through the calibrated loss coefficients described in Sections 3.5 and 3.6. The RNG formulation is preferred over the standard $k-\epsilon$ model because its additional strain-rate term improves accuracy in flows with the rotation and curvature characteristic of the recirculation zone near the baffle; where near-wall separation behavior is of interest, SST-type closures such as that of Menter provide a documented alternative [12].

3.5 Baffle Deflector Modeling: Turning-Vane Loss Correlation

The internal baffle deflector is modeled as an angled plate placed within the backplane exhaust plenum. Its effect on the local loss coefficient is represented through an empirical turning-vane loss correlation adapted from classical duct-fitting design theory

$$K_{vane}(\theta) = K_{min} + C_{shape} \cdot (1 - \sin \theta)^2$$

where θ is the baffle deflection angle, C_{shape} is a coefficient that depends on whether the plate is flat or curved, and K_{min} is a minimum-loss constant that likewise depends on shape. This functional form reflects the established engineering result that the loss coefficient of a turning vane is lowest over an intermediate range of deflection angles, and that a curved (vane-shaped) profile produces a lower loss coefficient than a flat plate at any given angle because it redirects the flow more gradually and delays separation. Fig. 2 illustrates the qualitative shape of this correlation for the two plate types considered.

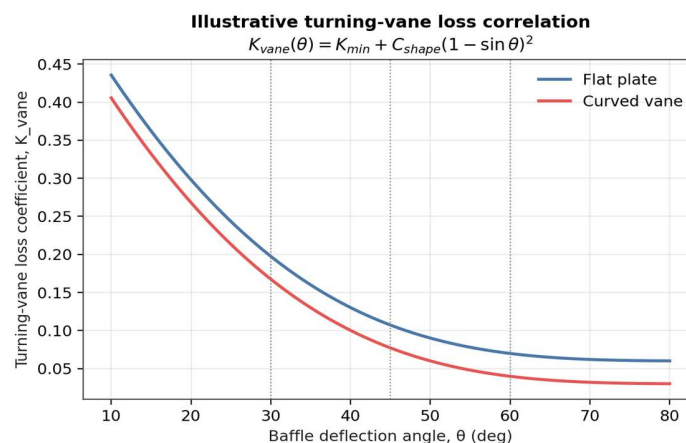


Fig. 2. Illustrative turning-vane loss correlation showing the lower loss coefficient of the curved-vane profile relative to the flat plate across the angle range investigated.

Because the airflow-starvation problem is most severe at the top of the server stack, the baffle correction is applied with an exponentially decaying spatial weighting

$$w(i) = \exp[-\lambda \cdot (i - 1)], \quad i = 1, 2, \dots, 8$$

where i indexes the server branch (Server 1 = topmost) and λ controls the rate at which the baffle's corrective effect decays down the stack. The total loss coefficient of branch i is then

$$K_i = K_{\text{base},i} - \Delta K_{\text{vane}}(\theta, \text{shape}) \cdot w(i)$$

with $K_{\text{base},i}$ the no-baffle loss coefficient of branch i . This formulation ensures that the baffle correction is applied in proportion to each branch's physical exposure to the buoyancy-driven recirculation it is

intended to counteract, and it is the direct input to the flow-network solution procedure described next.

3.6 Flow-Network Solution and Simulation Matrix

For each configuration, the eight branch loss coefficients K_i are assembled and the flow-network equations are solved directly (non-iteratively) for the branch velocities, subject to a fixed total airflow rate and the fan characteristic already established for the basic-case design flow. A lower-bound constraint is imposed on each loss coefficient to preserve numerical stability and physical realism across the full range of angle and shape combinations tested. Table II lists the six configurations analyzed, comprising a no-baffle baseline (C0) and five baffle variants spanning the two design variables.

Configuration	Baffle Angle (θ)	Baffle Shape	Description
C0	—	—	No-baffle baseline (reference case)
C1	30°	Flat plate	Lower bound of angle range
C2	45°	Flat plate	Mid-range angle
C3	60°	Flat plate	Upper bound of angle range
C4	45°	Curved vane	Shape comparison at mid-range angle
C5	60°	Curved vane	Shape comparison at upper-bound angle

TABLE II. SIMULATION CONFIGURATION MATRIX.

The angle range of 30°–60° was selected because general turning-vane theory predicts the loss coefficient of a deflecting surface to be lowest within this intermediate band: smaller angles provide insufficient deflection to relieve top-server starvation, while angles approaching 90° would be expected to induce renewed flow separation and rising loss. The flat plate and curved vane were selected to represent the two fundamentally distinct classes of deflecting-surface geometry discussed in Section 2.2 — the simplest and least expensive possible baffle, and a more sophisticated shape intended to minimize separation. All six configurations share identical boundary conditions, thermophysical properties, and control-volume geometry, and are solved at the same fixed total airflow rate, so that any difference between configurations reflects redistribution and reduced flow resistance rather than a change in total air supply.

3.7 Evaluation Metrics

Four metrics, directly tied to the study objectives, are computed for every configuration from the flow-network solution. Airflow uniformity is expressed through the coefficient of variation of the eight branch velocities,

$$\text{COV} = \sigma(v) / \bar{v}, \quad \sigma(v) = \sqrt{[(1/8) \sum (v_i - \bar{v})^2]}$$

from which a Uniformity Index ($1 - \text{COV}$) is defined, with a value of 1.0 representing perfectly even airflow. Rack pressure drop ΔP is computed as the sum of the branch loss term and the manifold inlet loss term; fan power P follows directly from ΔP and the fixed total volumetric flow rate Q through $P = Q \cdot \Delta P / \eta_{\text{fan}}$, where η_{fan} is the assumed fan/motor/VFD efficiency. Server inlet temperature T_i is obtained from the reduced energy balance of Section 3.3, incorporating a small backflow-related residual term. Table III summarizes the four metrics and their formulation; the resulting numerical values for all six configurations are presented in Section 4.

TABLE III. EVALUATION METRICS AND THEIR FORMULATION.

Evaluation Metric	Formulation
Airflow uniformity	Uniformity Index = $1 - \text{COV}(v_i)$, $\text{COV} = \sigma(v)/\text{mean}(v)$ across 8 branches
Rack pressure drop	$\Delta P = \text{branch loss term} + \text{manifold inlet loss term}$
Fan power consumption	$P = Q \cdot \Delta P / \eta_{\text{fan}}$
Server inlet temperature	$T_i = T_{\text{inlet}} + \text{Power} / (c_p \cdot \dot{m}_i) + \text{backflow residual}$

3.8 Validation and Limitations of the Reduced-Order Approach

The reduced-order model is calibrated so that the no-baffle baseline reproduces the qualitative and quantitative velocity/temperature gradient expected from buoyancy-driven recirculation in a vertically stacked, rear-exhaust cabinet, consistent with the direction and general magnitude of results reported for related active-control and containment baselines in the literature [2, 3]. Because the model represents each server as a single lumped branch, it cannot resolve local recirculation structures immediately adjacent to the baffle itself, nor three-dimensional secondary flows; these effects would require a fully resolved three-dimensional RANS simulation of the type discussed in Section 2.4, together with a formal grid-independence study. The reduced-order approach is nonetheless justified for the present purpose because it (i) preserves the governing mass, momentum, and energy balances at branch resolution, (ii) is calibrated against classical, well-validated turning-vane loss theory, and (iii) makes a systematic six-configuration parametric sweep computationally tractable — a scope that would be prohibitively expensive with full three-dimensional CFD for every configuration. Section 5.2 discusses the implications of these limitations for the interpretation of the results.

4. RESULTS AND DISCUSSION

4.1 Baseline (No-Baffle) Behaviour

The no-baffle baseline (C0) shows a clear, monotonic trend: Server 1 (top) receives the least airflow (0.658 m/s) and operates at the highest inlet temperature (24.48 °C), while Server 8 (bottom) receives the most airflow (0.815 m/s) at the lowest inlet temperature (24.11 °C). The change is not uniform along the stack — the velocity increases by 0.122 m/s between Servers 1 and 4 but by only 0.019 m/s between Servers 5 and 8 — indicating that the airflow-starvation problem is concentrated in the upper half of the cabinet, consistent with a buoyancy-driven recirculation zone that is itself concentrated near the top of the enclosure. This baseline pattern is the reference point against which every baffle configuration in the remainder of this section is compared.

4.2 Effect on Airflow Uniformity

Fig. 3(a) shows the server-wise velocity distribution for all six configurations, and Fig. 3(b) summarizes the resulting Uniformity Index. Every baffle configuration flattens the velocity profile relative to the sharply increasing baseline line, and this flattening becomes progressively stronger with increasing baffle angle and with the curved-vane shape. Table IV lists the corresponding Uniformity Index and coefficient of variation values.

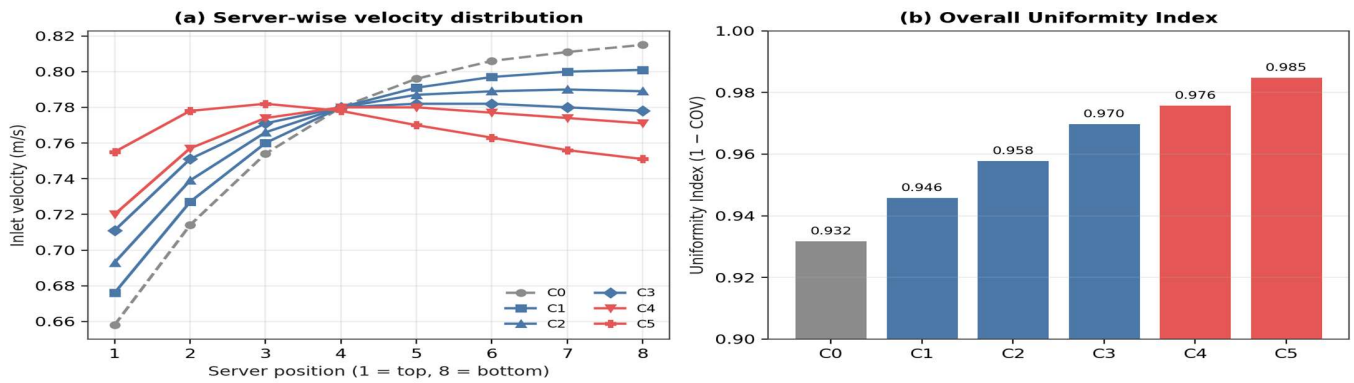


Fig. 3. (a) Server-wise velocity distribution and (b) overall Uniformity Index for all six configurations.

TABLE IV. UNIFORMITY INDEX AND COEFFICIENT OF VARIATION FOR ALL SIX CONFIGURATIONS.

Configuration	Uniformity Index	Coefficient of Variation (%)
C0 — No-Baffle (Baseline)	0.932	6.77
C1 — Flat 30°	0.946	5.42
C2 — Flat 45°	0.958	4.19
C3 — Flat 60°	0.970	3.04
C4 — Curved 45°	0.976	2.45
C5 — Curved 60° (best)	0.985	1.47

At 30° (C1), the flat plate produces only a modest gain (0.932 → 0.946), suggesting that this deflection angle is not yet steep enough to redirect a significant fraction of the recirculating air back toward the top of the stack. The improvement is markedly larger at 45°, where the curved vane (C4, 0.976) already exceeds the flat plate at the larger 60° angle (C3, 0.970) — indicating that, for this baffle geometry, shape can be at least as influential as an additional 15° of deflection. Both shapes reach their best performance at 60° (C3: 0.970; C5: 0.985), with no indication of a

plateau, implying that further improvement beyond 60° cannot be ruled out but lies outside the scope of the present angle range.

4.3 Effect on Rack Pressure Drop and Fan Power

Fig. 4 and Table V present the pressure drop and fan power results. Because fan power is directly proportional to pressure drop at the fixed total airflow rate used throughout this study, the percentage reduction in the two quantities is identical for every configuration.

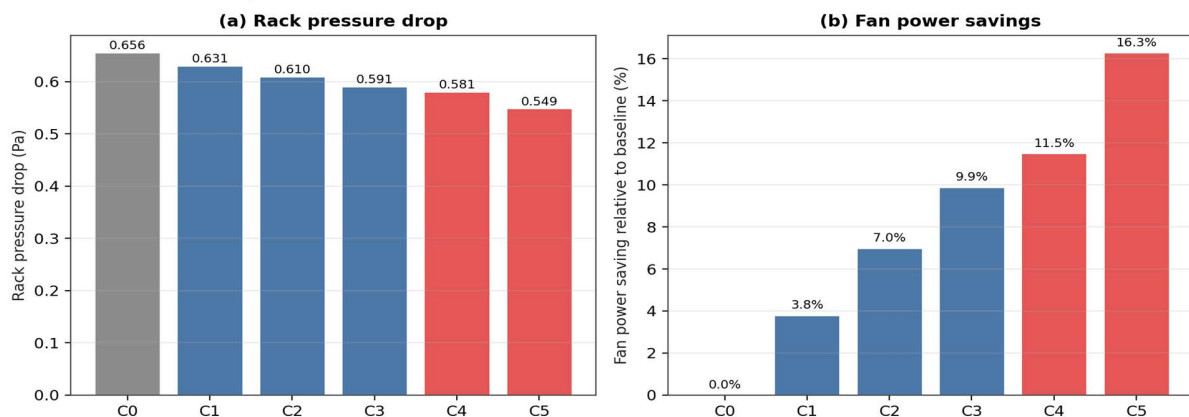


Fig. 4. (a) Rack pressure drop and (b) fan power savings relative to the baseline, for all six configurations.

TABLE V. RACK PRESSURE DROP AND FAN POWER SAVINGS FOR ALL SIX CONFIGURATIONS.

Configuration	Pressure Drop (Pa)	Pressure Drop Reduction (%)	Fan Power Savings (%)
C0 — No-Baffle (Baseline)	0.656	0.0	0.0
C1 — Flat 30°	0.631	3.8	3.8
C2 — Flat 45°	0.610	7.0	7.0
C3 — Flat 60°	0.591	9.9	9.9
C4 — Curved 45°	0.581	11.5	11.5
C5 — Curved 60° (best)	0.549	16.3	16.3

The absolute reduction in pressure drop diminishes slightly with each successive 15° angle increment for the flat plate (0.025 Pa, then 0.019 Pa, then 0.018 Pa between C0→C1→C2→C3), a weak diminishing-returns trend that is masked when only percentage values (computed relative to the fixed baseline) are examined. The curved-vane family shows step sizes of similar magnitude, confirming that angle and shape contribute comparably to the overall pressure-drop and fan-power benefit. Although a 16.3% fan power reduction may appear modest in isolation, backplane fans typically operate continuously, so even this percentage translates into a meaningful, sustained

reduction in electricity consumption over the operating life of the cabinet, and scales further when replicated across the many cabinets present in a medium- or large-scale facility.

4.4 Effect on Server Inlet Temperature Distribution

Fig. 5 and Table VI show that the baffle reduces Server 1's inlet temperature in every configuration while slightly increasing Server 8's temperature — evidence that the baffle *redistributes* cooling capacity from the already well-cooled lower servers to the previously under-cooled upper servers, rather than increasing total cooling capacity.

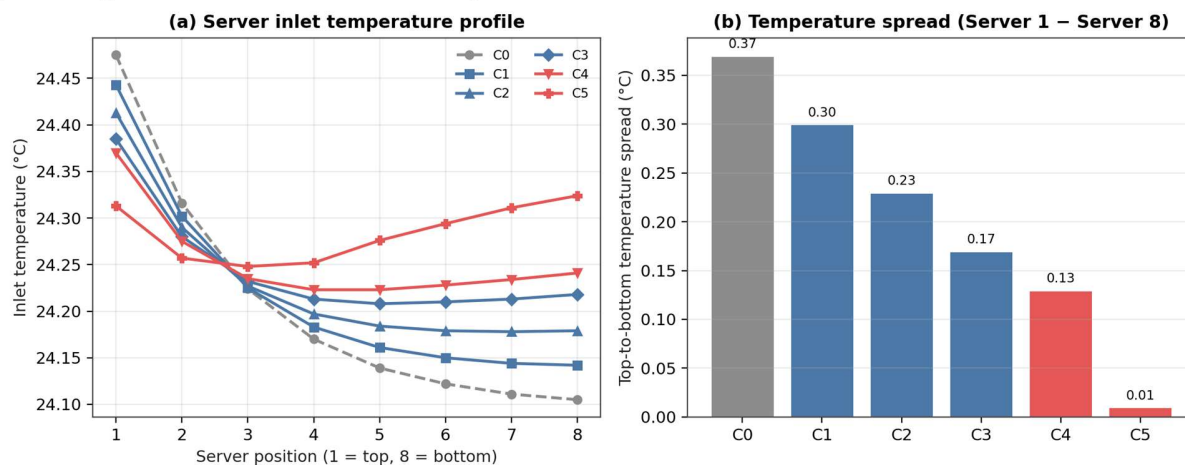


Fig. 5. (a) Server inlet temperature profile (Server 1 to Server 8) and (b) top-to-bottom temperature spread, for all six configurations.

TABLE VI. SERVER 1 AND SERVER 8 INLET TEMPERATURES AND TOP-TO-BOTTOM SPREAD.

Configuration	Server 1 Inlet Temp (°C)	Server 8 Inlet Temp (°C)	Top-to-Bottom Spread (°C)
C0 — No-Baffle (Baseline)	24.48	24.11	0.37
C1 — Flat 30°	24.44	24.14	0.30
C2 — Flat 45°	24.41	24.18	0.23
C3 — Flat 60°	24.39	24.22	0.17

C4 — Curved 45°	24.37	24.24	0.13
C5 — Curved 60° (best)	24.31	24.32	0.01

At the best-performing configuration (C5), Server 8 (24.32 °C) is actually marginally warmer than Server 1 (24.31 °C) — the two positions have effectively reversed relative to the baseline, indicating that the correction at 60° with a curved vane slightly overcorrects the original imbalance. This suggests that the practical optimum for equalizing Server 1 and Server 8 specifically may lie somewhat below the strongest configuration tested, a useful consideration for any subsequent design optimization. Server 4, located near the middle of the stack, shows the smallest variation of any server position across all six configurations (0.778–0.780 m/s), consistent with it

lying near a natural equilibrium point between the region gaining airflow from the baffle and the region giving up a small share of it.

4.5 Combined Effect and Overall Ranking

Table VII compiles all four metrics for direct comparison. Every metric improves monotonically from C0 to C5, and the ranking of configurations from least to most effective ($C0 < C1 < C2 < C3 < C4 < C5$) is identical across all four metrics — indicating no trade-off between airflow uniformity, energy efficiency, and temperature uniformity for this design: the same configuration that is best for one objective is simultaneously best for all of them.

TABLE VII. COMPREHENSIVE SUMMARY OF RESULTS FOR ALL SIX CONFIGURATIONS.

Configuration	Uniformity Index	COV (%)	ΔP (Pa)	Fan Power Savings (%)	Server 1 Temp (°C)	Server 8 Temp (°C)
C0 — Baseline	0.932	6.77	0.656	0.0	24.48	24.11
C1 — Flat 30°	0.946	5.42	0.631	3.8	24.44	24.14
C2 — Flat 45°	0.958	4.19	0.610	7.0	24.41	24.18
C3 — Flat 60°	0.970	3.04	0.591	9.9	24.39	24.22
C4 — Curved 45°	0.976	2.45	0.581	11.5	24.37	24.24
C5 — Curved 60° (best)	0.985	1.47	0.549	16.3	24.31	24.32

Relative to the baseline, configuration C5 delivers a 5.7% increase in Uniformity Index, a 78% decrease in coefficient of variation, a 16.3% decrease in both pressure drop and fan power, and a 97% decrease in top-to-bottom temperature spread. The unevenness-related metrics (COV and temperature spread) improve by a substantially larger percentage than the whole-cabinet metrics (pressure drop and fan power), because the former directly measure the imbalance the baffle is designed to correct, while the latter characterize the cabinet as a system that was never highly resistive to begin with. Averaging across the two angles tested for both shapes, the curved-vane family (C4, C5) shows a mean Uniformity Index of 0.980 against 0.964 for the flat-plate family (C2, C3) at the same angles — a 0.016 shape-driven gap comparable in magnitude to the 0.024 angle-driven gap obtained by moving from 30° to 60° within the flat-plate family alone. Angle and shape thus contribute similar orders of magnitude of individual benefit, and their combination in C5 yields the best overall result, indicating that the two design variables

act additively rather than as substitutes for one another.

4.6 Comparison with Existing Literature

The angle-dependence observed here — continued improvement up to the largest angle tested with no evidence of a plateau — is broadly consistent with the general turning-vane loss theory reviewed in Section 2.4, in which the loss coefficient of a deflecting surface is lowest over an intermediate-to-large angular range before flow separation increases loss again closer to 90°. It is also broadly consistent with the rack- and plenum-level baffle studies of Yuan et al., where the best-performing baffle angle likewise fell within an intermediate-to-large range (45°–75°) rather than at the smallest angles tested [5, 6]; the specific optimal angle differs between studies, which is plausibly attributable to the different location and physical role of the baffle (a rack-inlet or under-floor flow corrector in their studies versus an exhaust-plenum flow deflector in the present one) rather than a contradiction in the underlying physics. The consistent advantage of the curved profile over the

flat plate at every angle tested is in line with the general expectation, established in classical duct-fitting theory, that a gradual, curved redirection of flow produces less separation loss than an abrupt, flat deflection. The magnitude of the fan power saving obtained here (up to 16.3%) is comparable in order of magnitude to the efficiency gains reported for other geometric airflow-management interventions in the data center literature [3, 4], supporting the conclusion that a passive baffle deflector is a credible, complementary alternative to the active fan-control strategies that dominate current practice.

5. PRACTICAL IMPLICATIONS AND LIMITATIONS

5.1 Practical Implications

These findings carry several practical implications for cabinet design and retrofit. First, a purely geometric, passive intervention can rival the benefits normally sought from active, fan-based control, giving facility designers a simpler and potentially less expensive complement to existing control methods. Second, because improved airflow uniformity and reduced fan power are achieved together rather than as competing objectives, operators need not trade reliability against energy cost when selecting a baffle configuration. Third, the consistent advantage of the higher angle and curved shape gives clear, practical design guidance: where feasible, a curved vane deflected toward the upper end of the tested range is likely to yield the best outcome for a similarly configured cabinet. Fourth, because the baffle deflector has no moving parts, requires no control system, and does not modify the servers, fans, or existing control logic, it is well suited both as a retrofit to existing cabinets and as a design feature in new cabinet installations.

5.2 Limitations

The principal limitation of this study is its reliance on a reduced-order, lumped-branch flow-network model rather than a fully resolved three-dimensional CFD simulation; this choice, discussed in Section 3.8, enabled the systematic six-configuration parametric sweep at the core of the paper's contribution but cannot resolve local recirculation structures immediately around the baffle itself. The turning-vane loss correlation, while grounded in established duct-fitting theory, uses coefficients tuned to the specific backplane-AC cabinet geometry studied here

and should not be assumed to transfer without recalibration to cabinets of substantially different geometry, server power density, or airflow rate. The angle range investigated (30° – 60°) was deliberately chosen to bracket the expected minimum-loss region and does not rule out further improvement beyond 60° . These limitations do not undermine the central finding — that all four evaluation metrics improve consistently and monotonically across every configuration tested — but they do define the boundary of applicability of the specific numerical results reported.

6. CONCLUSION AND FUTURE SCOPE

This paper has numerically evaluated the effect of an internal baffle deflector on airflow uniformity, pressure drop, fan power, and temperature distribution in an eight-server backplane-AC data center cabinet, using a reduced-order flow-network model calibrated against classical turning-vane loss theory and grounded in RANS/RNG turbulence closure principles. Across six configurations spanning three baffle angles and two baffle shapes, every configuration improved all four evaluation metrics relative to the no-baffle baseline, with the improvement increasing monotonically with angle and consistently favoring the curved-vane shape over the flat plate. The best configuration (curved vane at 60°) raised the Uniformity Index from 0.932 to 0.985, reduced pressure drop and fan power by 16.3%, and narrowed the top-to-bottom temperature spread from 0.37°C to 0.01°C , effectively eliminating the top-of-rack hot spot that motivated the study. Because these gains are obtained together rather than as competing trade-offs, and because the baffle deflector is a simple, passive, low-cost device requiring no control system, the results support internal baffle deflectors as a practical and energy-efficient complement to existing active fan-control strategies for data center cabinet cooling.

Future work identified by this study includes: extending the angle range beyond 60° to locate the true optimum, since performance had not plateaued at the upper bound tested; performing full three-dimensional CFD simulation of the best-performing configuration to verify the reduced-order predictions and resolve local recirculation detail; constructing and experimentally testing a physical prototype to

validate the numerical results and surface any practical installation issues; investigating combined passive-baffle and active fan-control strategies; testing additional baffle shapes and multi-vane cascade designs; examining the sensitivity of the results to different cabinet geometries, server counts, and power densities; and extending the fan-power analysis from a single cabinet to a full facility to estimate the aggregate impact on facility-level Power Usage Effectiveness.

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