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Architectural Studies of Air Flow at Amoy Gardens, Kowloon Bay, Hong Kong, and its Possible Relevance to the Spread of SARS

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Dr. Tsou, Jin-yeu
Professor of Architecture
Chinese University of Hong Kong
e-mail: jinyeutsou@cuhk.edu.hk

Executive Summary

The scope of our work is to study, by means of computational fluid dynamics (CFD), the potential for air, water vapor, and airborne particulate matter (PM<10) to circulate from one flat to another. We limit our scope to the study of air flow around and through the building blocks, especially within the narrow “reentrant spaces” (also called “light wells”). The reentrant space – the indentation of the building plan between adjacent flats – is an important feature of most Hong Kong housing blocks. Most kitchen and bathroom windows and exhaust vents are located in such spaces. Previous studies have revealed the potential for exhaust air from one flat to enter neighboring flats through a shared reentrant space.

We are not aware of any evidence that the SARS virus is airborne, and do not attempt to address that issue. However, if others determine that the virus may be carried by air or water vapor, then studies such as this may be useful to investigate the correlation between air flow and disease spread. Thus, our study is motivated by three principal questions:

a. What characteristics of Amoy Gardens might contribute to the spread of an air-borne or vapor-borne pathogen?

b. How prevalent are these characteristics at other sites in Hong Kong?

c. What design modifications or retrofit construction would reduce the exchange of air and water vapor between flats?

Soon after the SARS outbreak was recognized, questions were raised as to whether the virus might be airborne or transmitted through air movement. To examine this hypothesis, we have developed a series of CFD models and run a set of simulations that

中國香港
沙田香港
中文大學
建築學系

DEPARTMENT OF ARCHITECTURE · THE
CHINESE UNIVERSITY OF HONG KONG
5TH FLOOR WONG FOO YUAN BUILDING
SHATIN · NT · HONG KONG SAR · CHINA
TEL +852 2609 6517 FAX +852 2603 5267
E-MAIL ARCHITECTURE@CUHK.EDU.HK

consider the clustering and form of the building blocks, the openings into the reentrant space, the surrounding wind patterns, water vapor, and airborne particulate matter – especially, dust from the neighboring construction site.

The outcomes of this investigation supplement the report of the Government of the Hong Kong Special Administrative Region (HKSAR), regarding the environmental aspects that contributed to the outbreak of SARS in Amoy Gardens Block E*.

We submitted our preliminary findings to the HKSAR Department of Health on the 16th of April. Since then, we have conducted further studies to examine various scenarios and further validate our model. Our aims are to contribute to the understanding of inter-flat movement of air and water vapor as possible factors in disease spread, and to investigate the potential of alternative designs to improve the ventilation of reentrant spaces.

This study indicates that the flow pattern in the reentrant space between Units 7 and 8 of Block E has the potential to transport air and water vapor from one flat to another. This flow is mainly influenced by three factors: the dimensions and proportions of the reentrant space; the orientation of the reentrant space with respect to the prevailing wind; and the "curtain" effect caused by the rapid horizontal air movement across the mouth of the reentrant, through the gap between Blocks E and F. Our simulations indicate that changing these factors, through redesign or retrofits, could improve the ventilation of the reentrant space dramatically.

If air movement contributes to the virus distribution, then an important question is whether other housing blocks have configurations similar to Amoy Gardens Block E. Could a similar set of conditions lead to an Amoy-style outbreak elsewhere? The combination of factors is crucial to the development of the air flow pattern, and the particular combination observed at Amoy Gardens is rare. Furthermore, subsequent to the construction of Amoy Gardens, the building code regulating the design of reentrant spaces has been revised to improve their ventilation.

1. High Density Housing, Building Codes, and Reentrant Design

The outbreak of SARS has highlighted the need for critical attention to the design of housing in Hong Kong's extreme high density environment. This extreme density, with apartment blocks of 30 to 50 stories standing shoulder to shoulder throughout the city, is a relatively recent development. Appropriate housing and planning policies, environmental guidelines, and space standards for such settings are still evolving. In most other cities, the pattern of air movement from one window to a neighboring one, the leak in a drainage pipe, the closed air of an elevator lobby, would each have a minimal and readily identifiable effect. But with increasing density come increasing

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* "Outbreak of Severe Acute Respiratory Syndrome (SARS) at Amoy Gardens, Kowloon Bay, Hong Kong: Main Findings of the Investigation." Department of Health, Hong Kong Special Administrative Region, 17 April 2003.

interaction and overall system complexity. In these conditions, a minor failure can initiate a cascade that reaches far beyond the initial fault. The SARS crisis makes this point painfully clear. The policies that regulate and guide the future of housing and the development of the city ought to embody a better informed and more far-sighted vision than what has thus far directed the shaping of Hong Kong. It is our mission to contribute effectively to the formulation of those policies.

The "reentrant space" – a semi-open light well open to the air on one side – has been a common feature of high rise residential blocks in Hong Kong over the past few decades. This has developed out of the demand for a very compact floor plate design for residential towers, which typically house four to eight apartments on each floor (even up to ten in some cases). Developers aim for a highly efficient arrangement with the highest possible gross-to-net floor ratio. Thus, they put the public service elements, such as lifts, fire escape staircases, electricity ducts, and public access corridors, into a compact central core to reduce such service areas to the bare minimum, and arrange the apartments (the saleable portion) to the periphery. In order to put as many of the "habitable" rooms to the outermost periphery zone as possible, the toilets, kitchens, and secondary spaces such as store rooms, have been grouped around slots of light wells, the "reentrants", to gain the necessary access to the open air. This leaves the other "habitable" rooms (such as living room, bedrooms, dining room) to enjoy the best possible peripheral view. The Buildings Ordinance in Hong Kong requires the provision of windows for natural lighting and ventilation of facilities such as toilets and kitchens, and those have been satisfied by having the required windows opening to the reentrant space, which must be vertically unobstructed and has a minimum prescribed width – 1.5 meters clear for cases with toilets only, or 2.3 meters clear for cases with kitchens [Building (Planning) Regulations]. The existing regulations specify only the minimum width, and make no reference to the depth or height of such reentrant spaces. This explains the very elongated light wells in typical Hong Kong high rise residential towers, which are becoming higher and higher over the years. Developers have also found this arrangement to be cost efficient in its concentration of all plumbing for water supply as well as drainage around a compact reentrant space, and usually leave such plumbing exposed outside the building.

Over the years there has already been much concern and many complaints from the public against such reentrant arrangements, particularly regarding the fact that fumes from toilets and kitchens enter adjoining flats on floors above and below. Also, clothes drying racks are usually located in these spaces, for access from kitchen and bathroom windows. This practice has often been questioned long before the SARS outbreak.

2. Amoy Gardens Background

Amoy Gardens is a fairly typical Hong Kong housing estate. It consists of 8 residential towers, 33 stories each, rising above a commercial and shopping center. There are 8 flats per floor arranged in a cruciform shape. Each arm of the cruciform contains 2 flats, partially separated by a reentrant space. Elevators and fire stairs comprise the core. Within the reentrants, bathroom windows and vents open in proximity to laundry drying racks as well as exterior plumbing – fresh water, sewage, and stack vents. (Kitchen windows and vents open to the opposite side.) In the summer, these spaces also receive significant waste heat and dripping from air conditioners. Depending on its orientation with respect to the sun and wind, a reentrant may be often shaded and poorly ventilated.

3. Hypothesis: Water Vapor and the Spread of SARS at Amoy Gardens

Following an intensive government investigation, the Hong Kong Department of Health [2003 April 17] reported that "transmission of the disease by airborne, waterborne route and infected dust aerosols have been examined but these were not supported by the epidemiological picture and laboratory results." Nevertheless, for a "probable explanation of the outbreak", the report stated:

> The bathroom floor drains with dried-up U-traps provided a pathway through which residents came into contact with small droplets containing viruses from the contaminated sewage. These droplets entered the bathroom floor drain through negative pressure generated by exhaust fans when the bathroom was being used with the door closed. Water vapour generated during a shower and the moist conditions of the bathroom could also have facilitated the formation of water droplets … Contaminated droplets could then have deposited virus on various surfaces, such as floor mats, towels, toiletries and other bathroom equipment.

If the low pressure difference induced by a typical bathroom exhaust fan is sufficient to pull contaminated droplets up from a sewage drain, around a dry U-trap, and into the inhabited space, then it seems likely that such droplets may be transported by other means as well. It is worth exploring other possible routes and contributing factors.

If the exhaust fans pulled contaminated droplets from the floor drains and into the inhabited space, then they almost certainly would also exhaust many of these droplets out to the reentrant space – that is what the fans are designed to do. Moreover, if they could lift droplets from the floor drain, then they could certainly expel droplets from an infected, coughing individual.

The government report also documented a "chimney effect" within the reentrant space, and hypothesized that it might even have been sufficient to carry contaminated droplets up from a cracked pipe at the 4th floor, although most of the infections occurred at floors 10 and above. If air flow in the reentrant space could transport droplets from a cracked pipe, it could also transport droplets coughed by an infected individual and expelled by an exhaust fan.

So, it seems probable that contaminated droplets entered the reentrant space. If air flow carried these droplets into other flats, this could be a significant path of disease spread, completely independent of the sewage system. We have focused on the flow of air and water vapor within these spaces, especially the space between units 7 and 8 of Block E – the units that suffered the "highest attack rates". Previous research on air flow in reentrant spaces has revealed recurring problems with exhaust air reentry from one flat to another.

The convergence of bathroom windows and exhaust vents, as well as damp laundry on racks, may substantially alter the temperature and humidity of the air in the reentrant space from ambient conditions. As the climate heats up, waste heat from air conditioners also becomes a significant factor in the air flow. (This was probably not a factor during the Amoy Gardens outbreak, but will become increasingly important in the weeks and months ahead.)

Although the government report dismissed the likelihood of widespread airborne transmission, it nevertheless acknowledged the possible contribution of the "chimney effect". Our hypothesis is that increased water vapor in the reentrant space might contribute to the air's ability to transport the virus between flats. This could comprise a path of infection completely independent of the sewage system. Furthermore, we propose that retrofits of existing structures, as well as building code revisions for new structures, could improve the ventilation of these spaces and mitigate the chances of a similar outbreak in the future.

4. Methodology: Computational Fluid Dynamics (CFD)

We have conducted a preliminary analysis of air flow in the vicinity of Amoy Gardens, using computational fluid dynamics (CFD). This is a well-established methodology, widely used in mechanical engineering, meteorology, and other disciplines.

It is not possible to solve directly the set of partial differential equations that govern complex fluid flows. CFD approximates the differential equations with algebraic equations applied to discrete cells in a mesh. Potential sources of error include:

- the mathematical models used to describe the airflow;
- the discretization of the mesh;
- iteration and computer round-off;
- initial inputs for geometry, atmosphere, and terrain.

Our selection of mathematical models, mesh system, iterations, and input aim to minimize these errors while producing useful results in a reasonable time. We conducted our simulations with Fluent 6.0 software, running on an IBM e-Server p-670 supercomputer.

Mathematical Models

We select the Reynolds Averaged Navier Stokes (RANS) equations and the RNG k-ε equations as the mathematical models for numerical simulation of air flow. To describe the water vapor concentration, because the density of air and water vapor are quite different, we use multi-phase concepts and consider the fluid as a granular flow. The partial differential equations are discretized into algebraic equations over the mesh system using the Finite Difference Method (FDM)

Mesh

The quality of the mesh is critical to the accuracy and stability of the numerical simulation. In defining the model, it is important to focus computational resources by using a finer mesh in areas of particular interest, and a coarser mesh in less critical areas. Our model focuses particular attention on Units 7 and 8 of Block E and the reentrant space between them. We have used several variations of a common base model to examine different aspects of the flow and to test alternative scenarios. The number of discrete hexahedral cells in these models ranges between 1.5 and 2.5 million. The maximum size ratio between adjacent cells is 1.2. In all, the buildings occupy a volume of 167 x 134 x 119 meters. The surrounding computational domain is 1800 x 1500 x 500 meters.

Iteration

To reduce computer round-off in the iterations, we used the double-precision (64-bit) version of the software.

Geometric Model

Figure 1 illustrates the geometric model. It includes Blocks A, B, C, D, E, F, G, and H of Amoy Gardens. These blocks are 105 meters high and situated on a podium 14 meters high. Blocks A-D and G-H are treated as simple cruciforms, without excessive detail. Blocks E and F are modeled in greater detail and include the reentrant spaces, which are 2 meters wide by 8 meters deep. All of the blocks except E are treated as solid masses through which no air can penetrate.

In Block E , we include interior spaces and partitions for flats 7 and 8 on floors 19 through 23. Within these flats: air cannot penetrate the internal walls; the internal doors are open; the entry doors of the flats are closed; the windows have 30% free area for air flow; fans are installed on the external walls of bathrooms. The fan performance is linear: when the pressure head is zero, the volume flow rate is 2 m^3/s; when the air speed is zero, the static pressure is 20 Pa. The vapor source in each bathroom releases 0.01 kg/s. The temperature of the vapor is not considered.

On the east side of Amoy Gardens, our model also includes a neighboring school and a large construction project for an elderly center. We treat the school as a solid mass. We assume that the building under construction has 50% free area for air flow.

We have also simulated hypothetical variations of the Amoy Gardens design, to examine the effects of changing the proportions of the reentrant space, and introducing exterior panels to help channel air through the space.

Atmosphere and Terrain

We use an atmospheric boundary layer to describe the incoming flow. The local terrain type is an urban area, for which we use a terrain factor exponent of 0.22. The thickness of the atmospheric boundary layer is 370 meters. The prevailing wind, as measured at the nearest weather station (Kai Tak) and reported by the Hong Kong Observatory for March 2003, was from the east-southeast (110º), with an average speed of 3.61 meters per second at a height of 16 meters. The turbulent intensity of the incoming flow is 10%.

To probe the effects of wind direction, we simulated winds from 110º, 95º, 66º, and 54º. These selections were influenced by the layout of the buildings.

We also simulated airborne particulate matter (APM), trying various dust sources: between Block E and the construction site; above the construction site; between Block E and the school.

5. Findings

Although all possible efforts have been made to insure its accuracy, the model depends on certain assumptions regarding site conditions, such as the prevailing wind, that have not yet been verified by direct measurement. Using the information available to us thus far, our simulations have produced these findings:

a. There is a wind-driven vertical flow in the reentrant space, affected mainly by the geometry of the reentrant and its orientation to the prevailing wind. The air in the reentrant space between Units 7 and 8 of Block E moves only slowly. The rapid horizontal flow across the mouth of the reentrant, through the narrow gap between Blocks E and F, produces an "air curtain" effect that impedes the ventilation of the reentrant space [Figures 2-4].

b. Because of the pressure difference between façades on opposite sides of a block, air tends to enter units on the upwind side, exit into the reentrant space, and enter adjacent units on the downwind side before finally exiting the block [Figures 5-7].

c. The bathroom windows, exhaust fans, and plumbing, as well as laundry racks, are located in the reentrant spaces of Block E (as is typical in Hong Kong housing blocks). Water vapor emitted from bathroom exhaust, clothes drying, and broken sewer pipes, can follow the air flow into adjacent flats [Figures 8-13].

d. Airborne particulate matter emitted from the neighboring high-rise construction project has the potential to travel from one flat to another [Figures 14].

e. Increasing the distance between openings and widening the proportions of the reentrant space could reduce the concentration of water vapor and mitigate the "exhaust air reentry" problem [Figures 15-16].

f. An airflow guiding panel near the edge of the reentrant space could improve the ventilation of this space. We have simulated several possible retrofit solutions, with consideration for constructability and affordability [Figures 17-18].

6. Relationship of CFD to Scale Model Wind Tunnel Tests

Digital CFD models and analog wind tunnel models play complementary roles in the study of air flow. Neither is inherently better than the other. Both are subject to the maxim: "garbage in, garbage out." In particular, the veracity of each simulation depends on accurate representations of inputs and boundary conditions.

Scale models are relatively easy to construct, are tactile, and are easily understood by laymen as well as professionals. The circulation of smoke around a scale model in a wind tunnel speaks for itself. Nevertheless, problems of scale can confound the veracity of the simulation. While one can easily scale the air speed in proportion to the dimensions of the model, one cannot easily scale the air's viscosity, the mass and diameter of suspended droplets, or the roughness of surfaces. These are all important factors in studying the boundary flows that predominate in the reentrant spaces. Moreover, the placement of smoke emitters, observers, and camera equipment in the air stream may invalidate the simulation.

Computational models are difficult to construct and interpret, and require sophisticated computer hardware and software to execute. However, they are free from problems of scale and observer interference. The dimensions of the building, the speed and viscosity of the air, and the mass and diameter of droplets exist at 1:1 scale in the virtual model. Observations are disembodied and do not interfere with the simulation. On the other hand, CFD is a finite element method, and it is often challenging to define and analyze models at a sufficiently high resolution. A reliable study may require millions of finite elements, gigabytes of memory, and billions of calculations per second. Our study models comprise from 1.5 to 2.5 million volumetric cells. We have defined and executed the simulation using Fluent 6.0 software on an IBM e-Server p-670 supercomputer.

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Mr. Benny Chow, Assistant Computer Officer, Department of Architecture, CUHK
Dr. Theodore W. Hall, Research Officer, Department of Architecture, CUHK
Prof. Bernard Lim, Professor of Architecture, CUHK

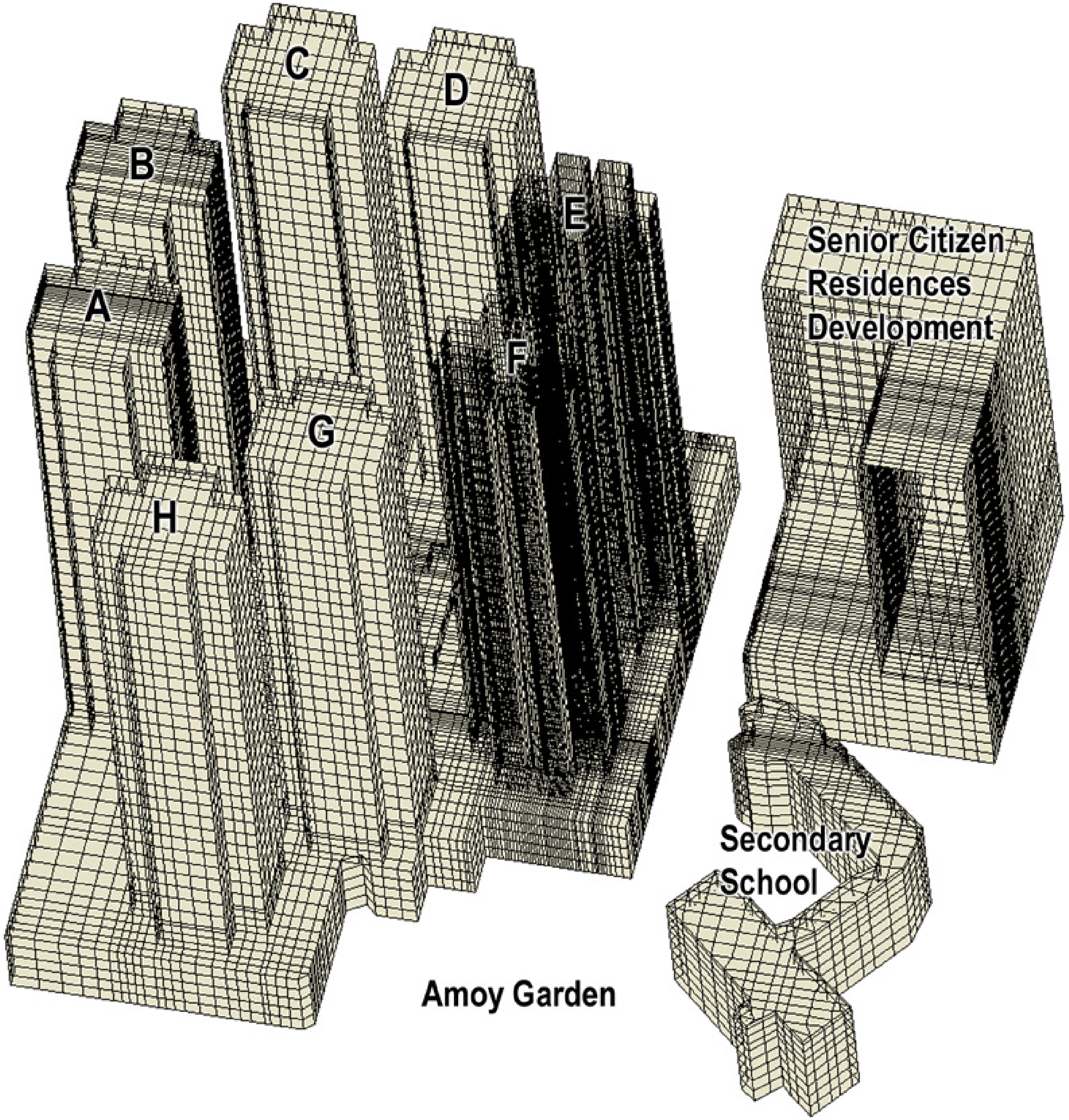
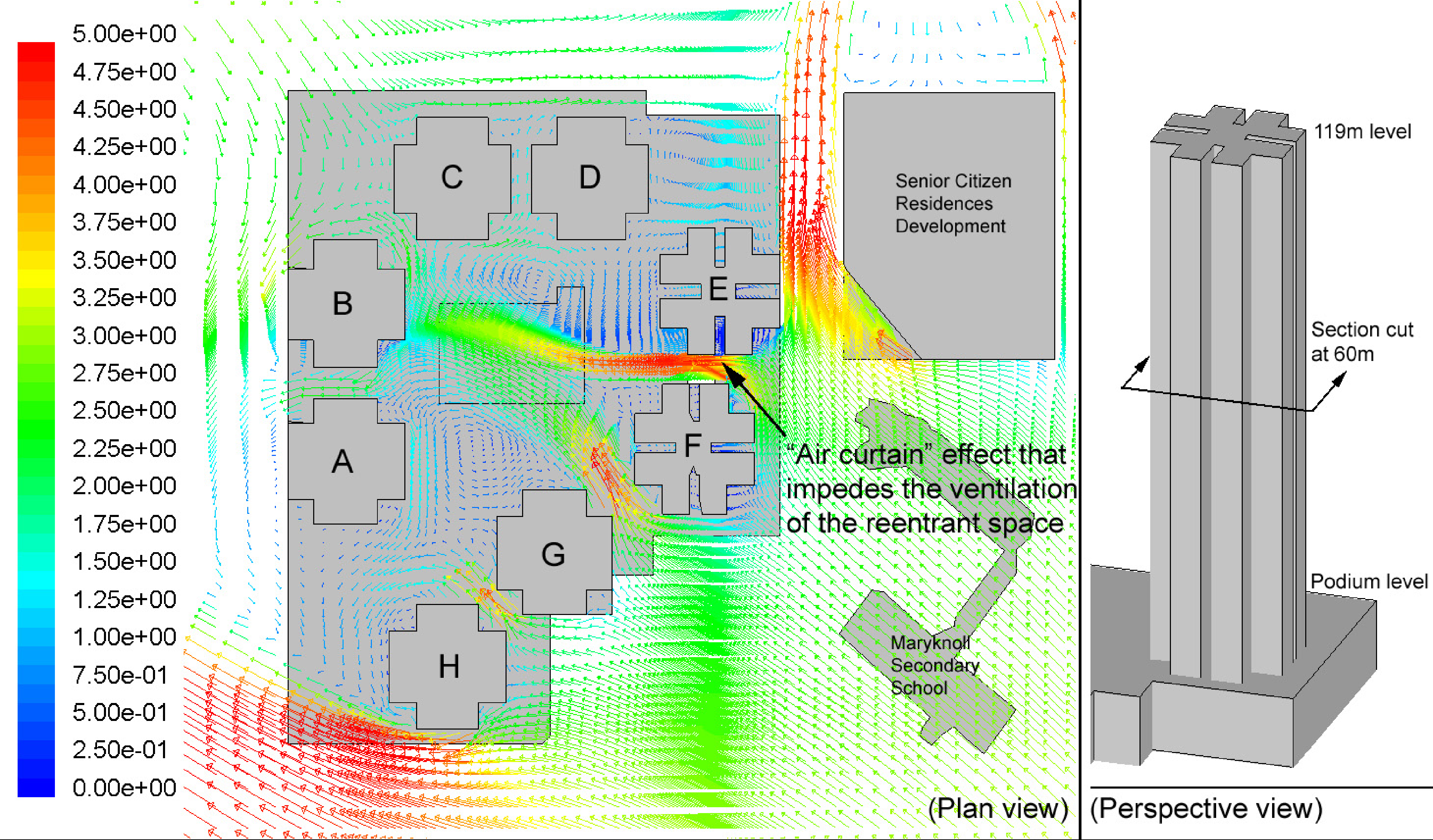


Figure 1: Geometric Model for Air Flow Study

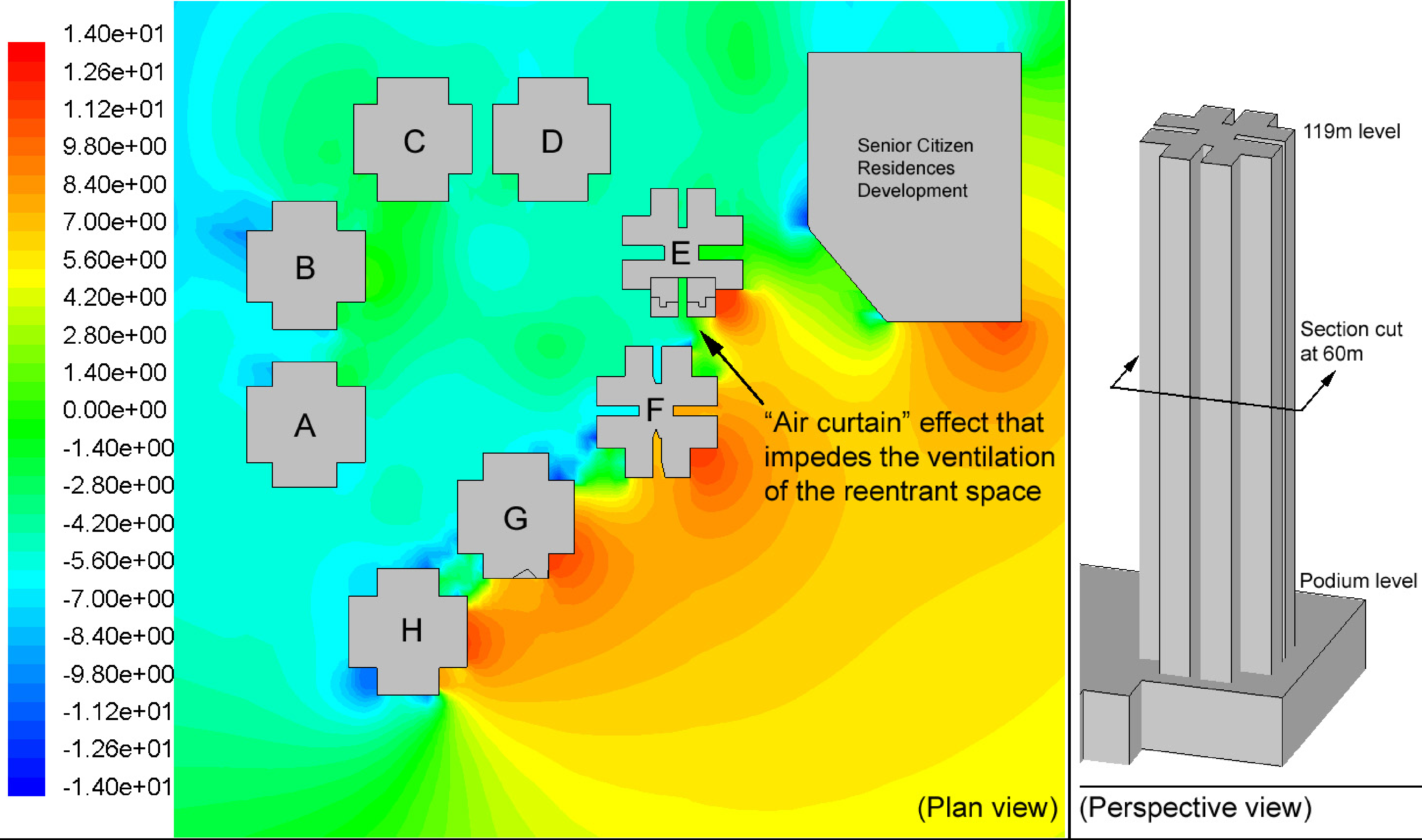


"Air curtain" effect that impedes the ventilation of the reentrant space

(Plan view)

(Perspective view)

Figure 2: Rapid Flow Across the Mouth of the Reentrant Space
(Velocity vectors colored by velocity magnitude (m/s), clip to 5m/s)



“Air curtain” effect that impedes the ventilation of the reentrant space

(Plan view)

(Perspective view)

Figure 3: Rapid Flow Across the Mouth of the Reentrant Space (Contours of Static Pressure (pascal), clip to -14Pa to 14Pa)

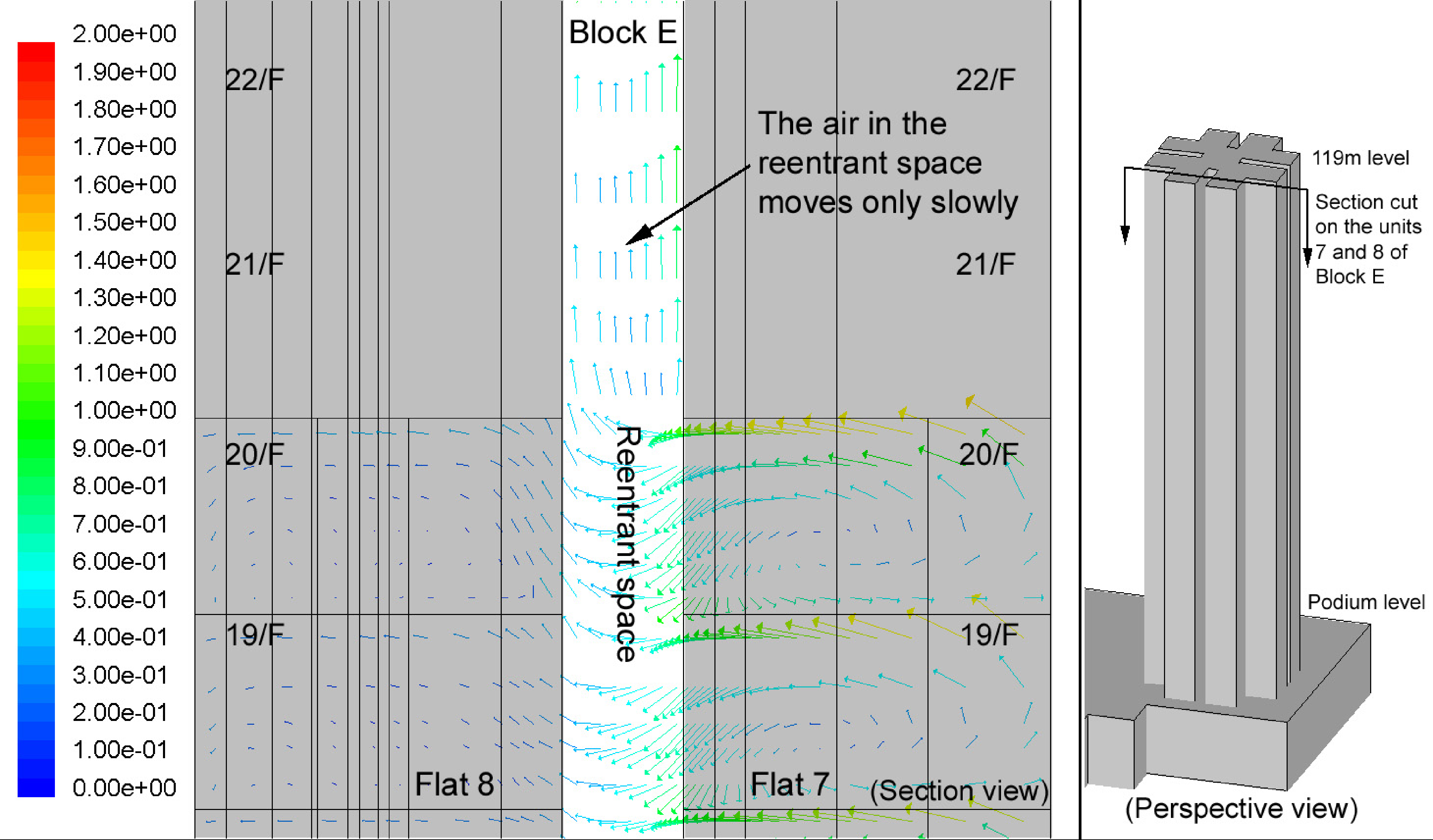


Figure 4: Slow Vertical Flow Within the Reentrant Space
(Velocity vectors colored by velocity magnitude (m/s), clip to 2m/s)

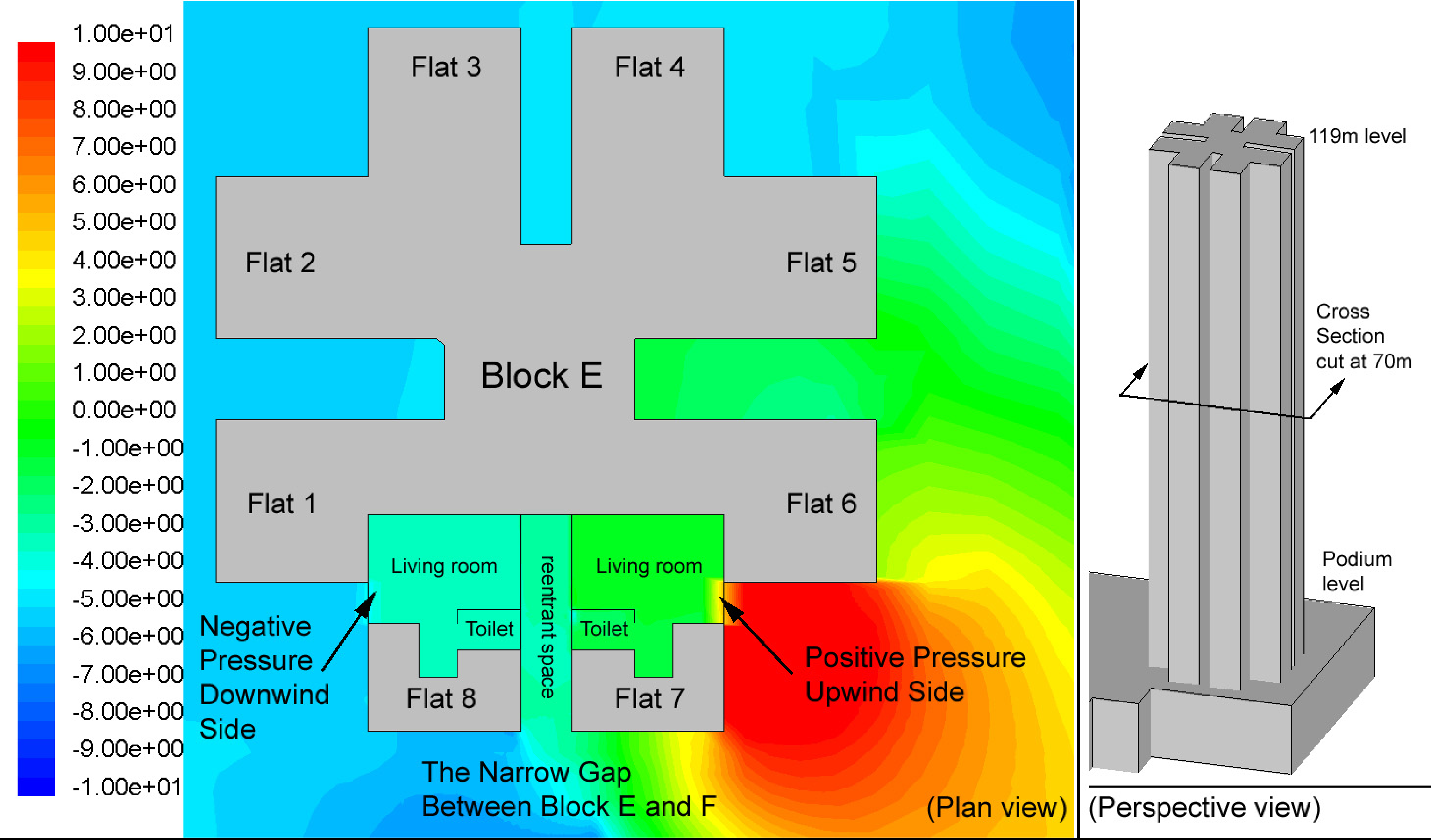


Figure 5: Air Flow Through Block
(contours of static pressure (pascal), clip to -10Pa to +10Pa)

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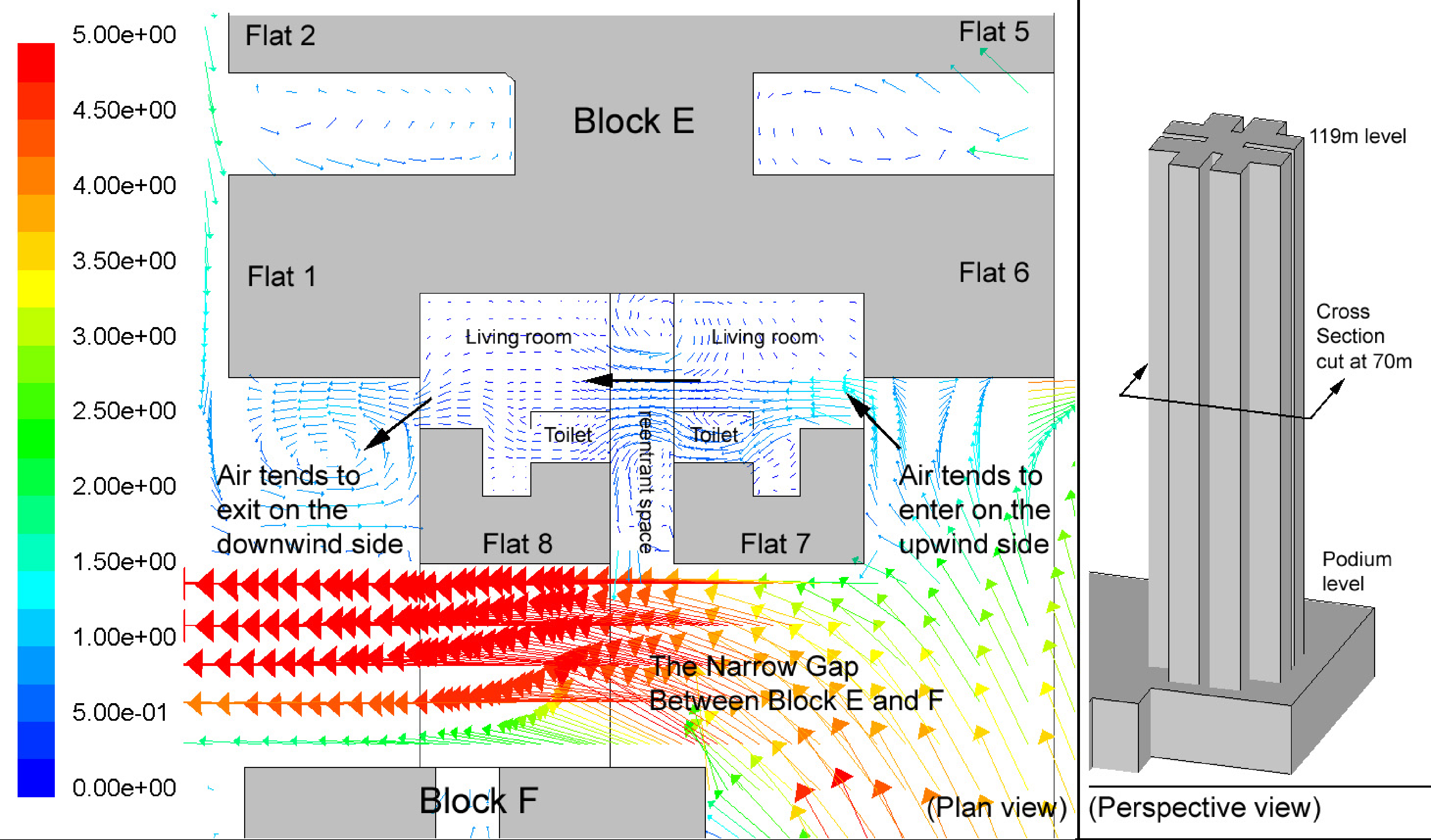

Figure 6: Air Flow Through Block
(Velocity vectors colored by velocity magnitude (m/s), clip to 5m/s)

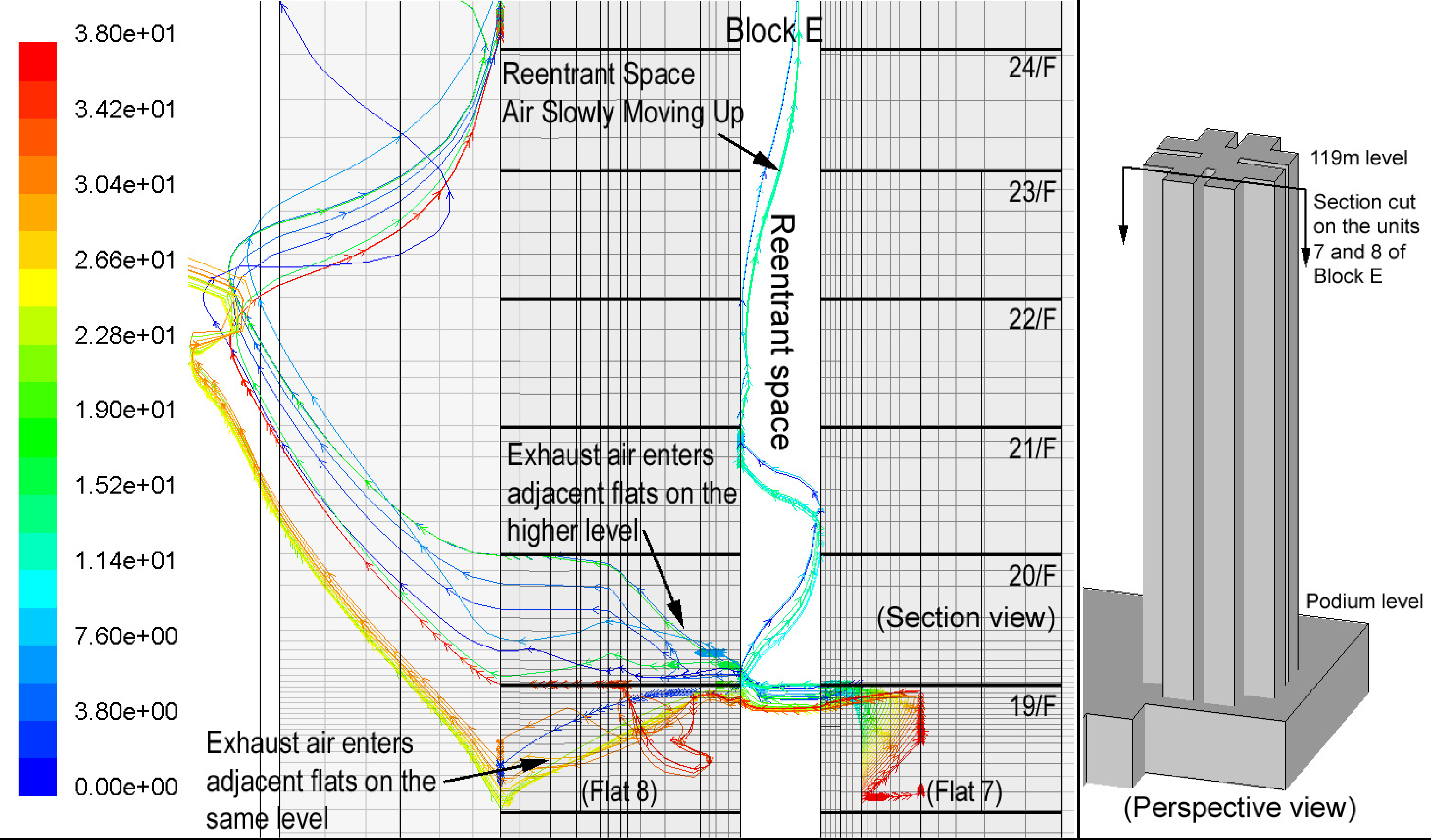

Figure 7: Air Flow Through Block and Slow Vertical Flow Within the Reentrant Space
(Path Lines Colored by Particle Id)

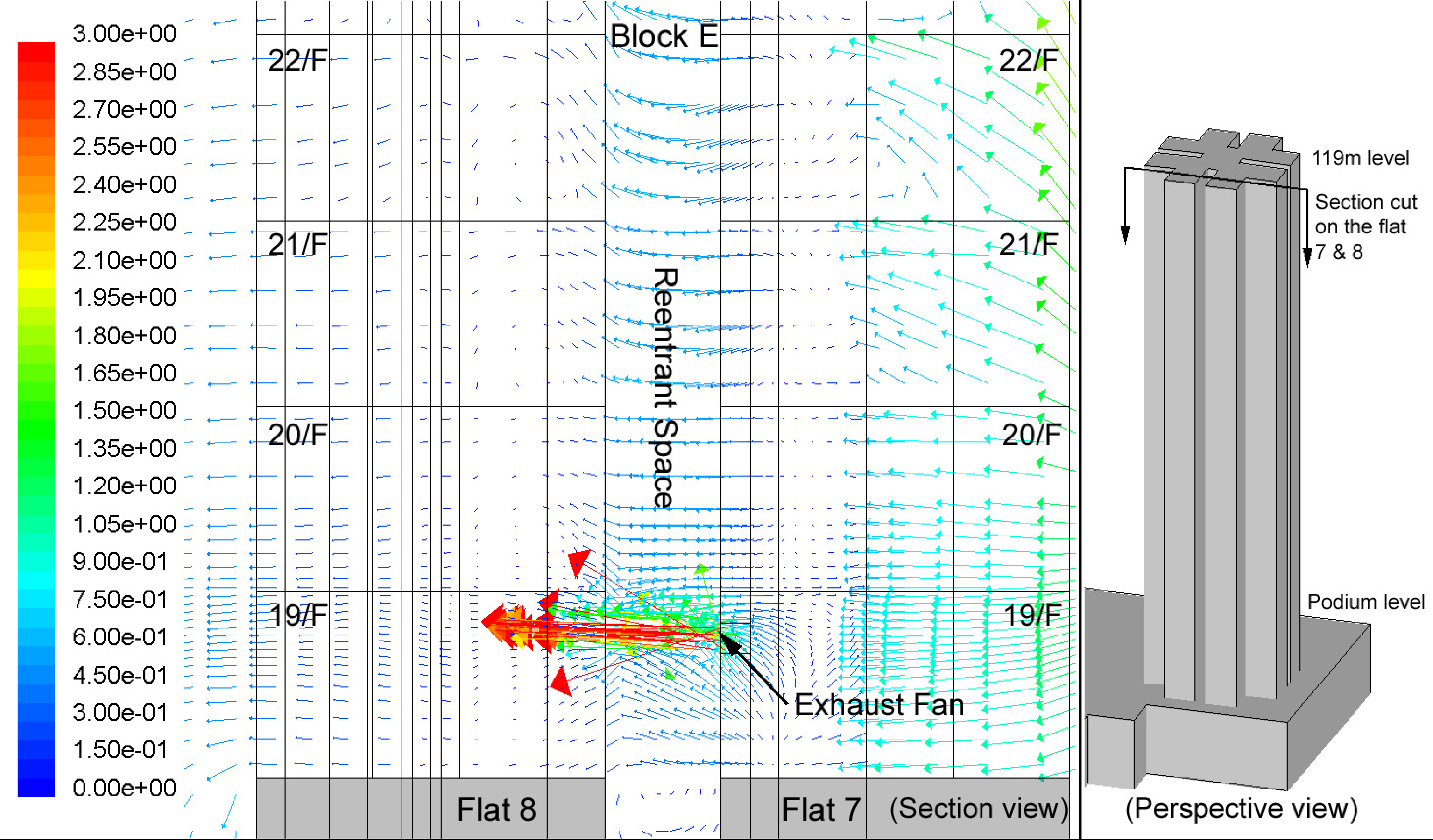

Figure 8: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Velocity vectors colored by velocity magnitude (m/s), clip to 3m/s)

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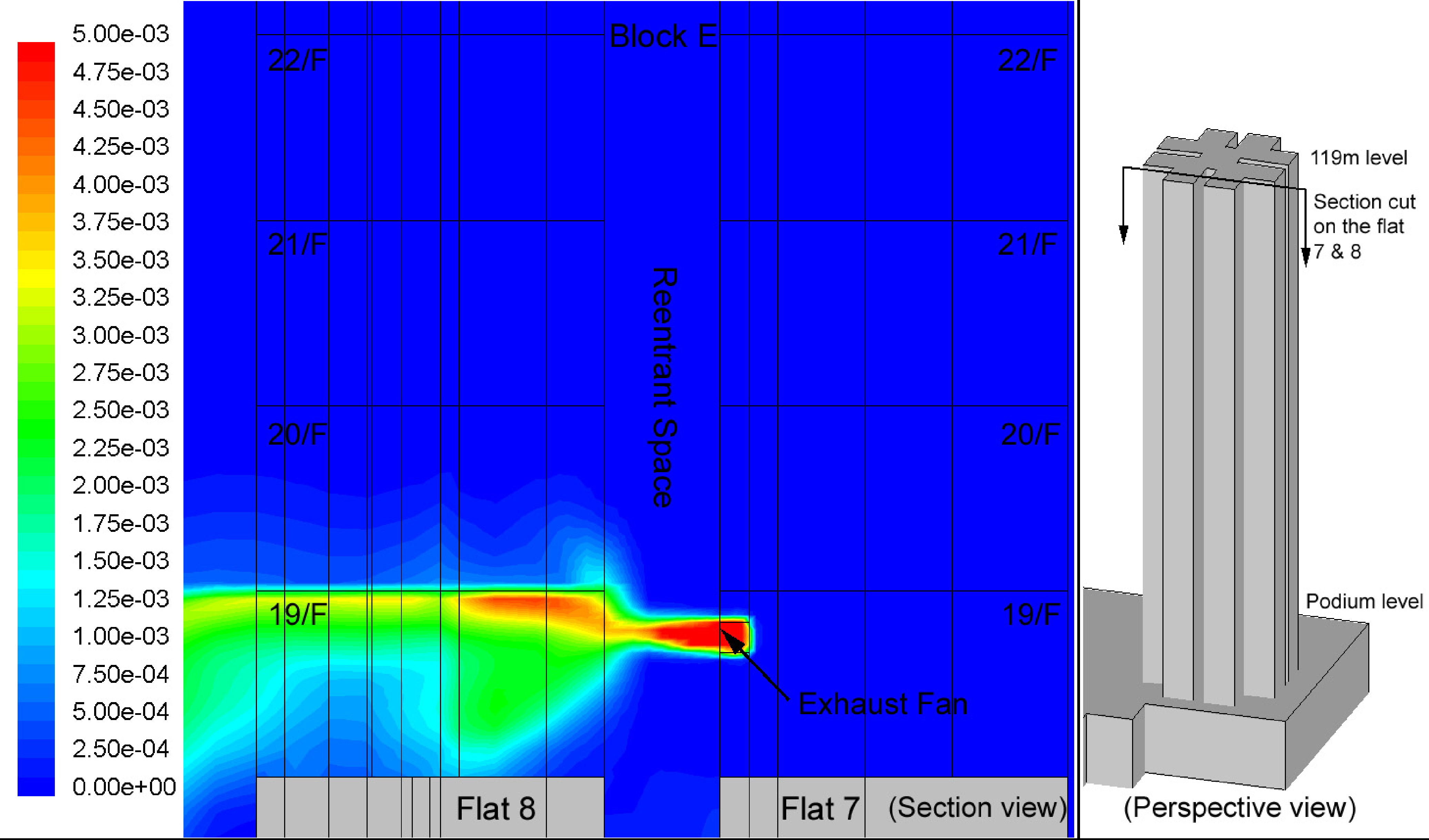

Figure 9: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Contours of mass fraction of water vapor)

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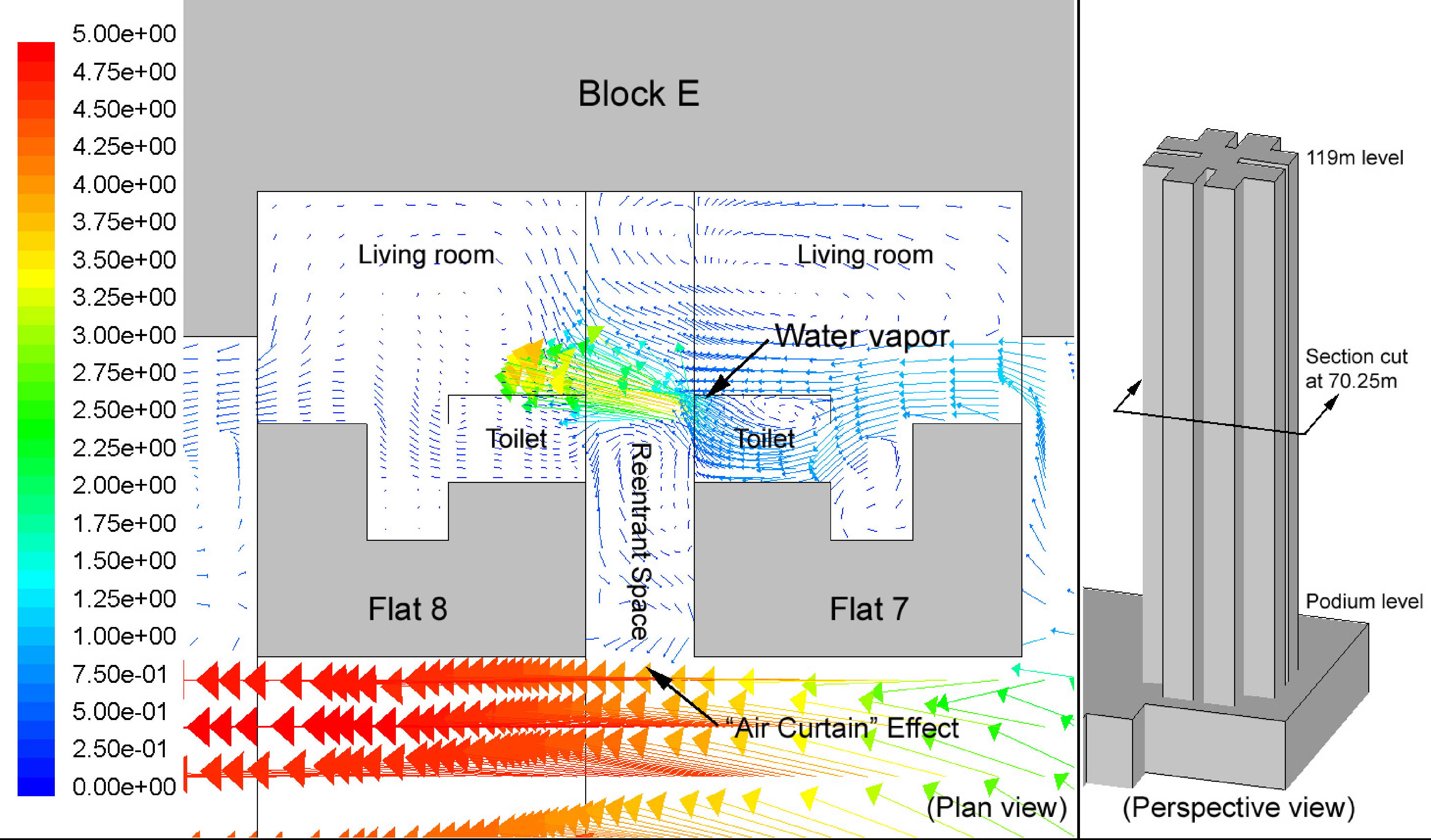


Figure 10: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Velocity vectors colored by velocity magnitude (m/s), clip to 5 m/s)

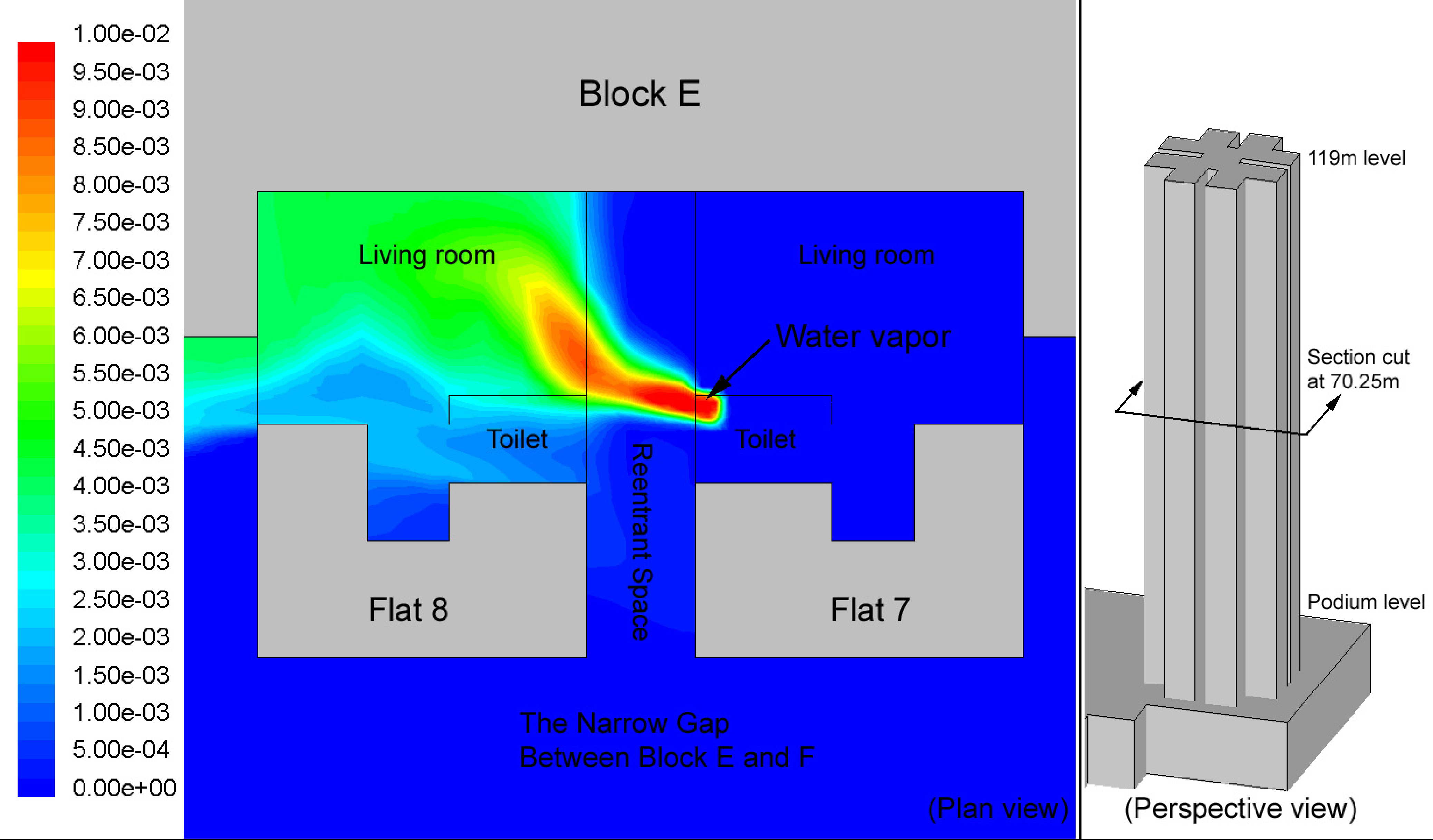


Figure 11: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Contours of mass fraction of water vapor)

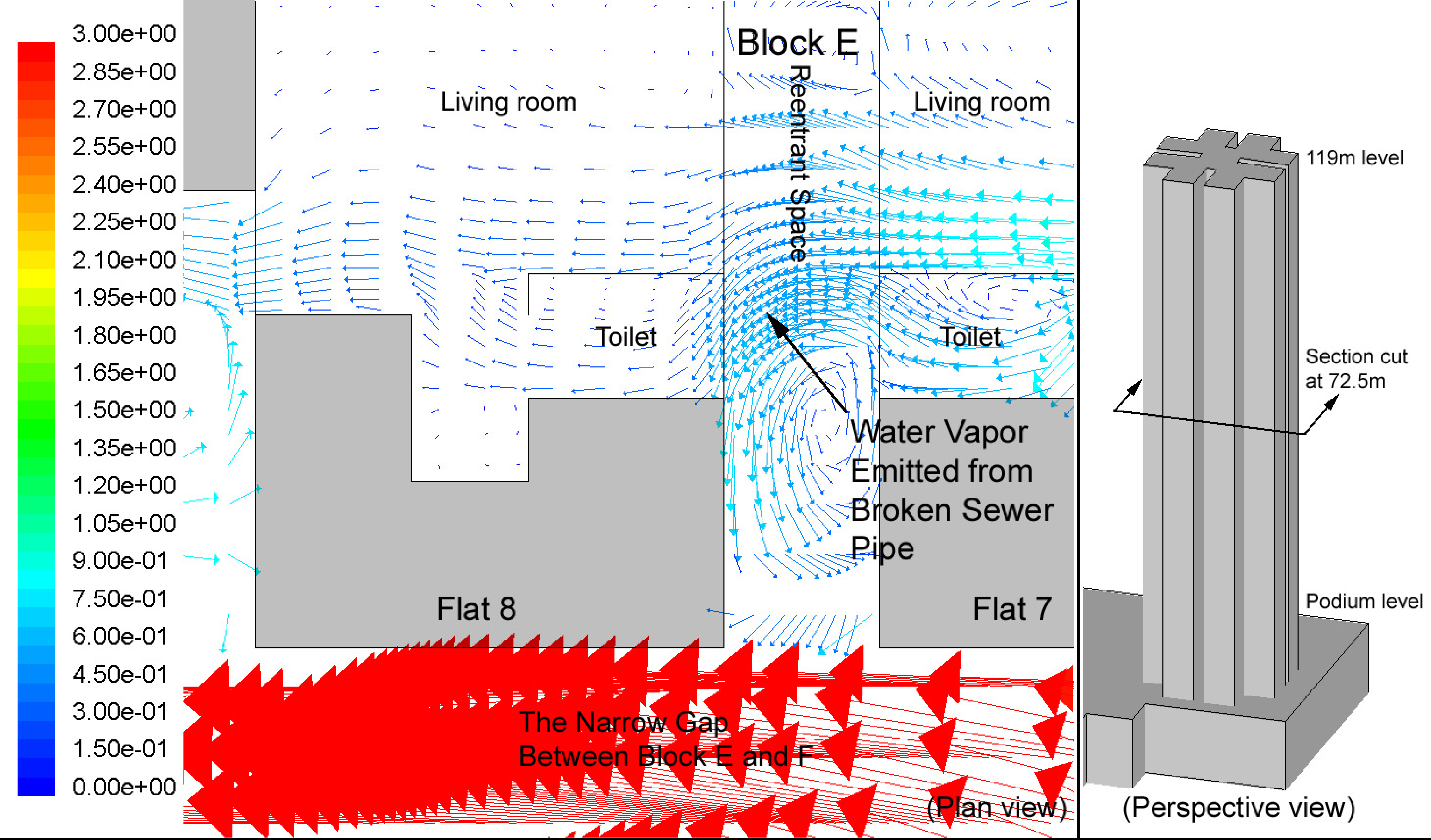


Figure 12: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Velocity vectors colored by velocity magnitude (m/s), clip to 3m/s)

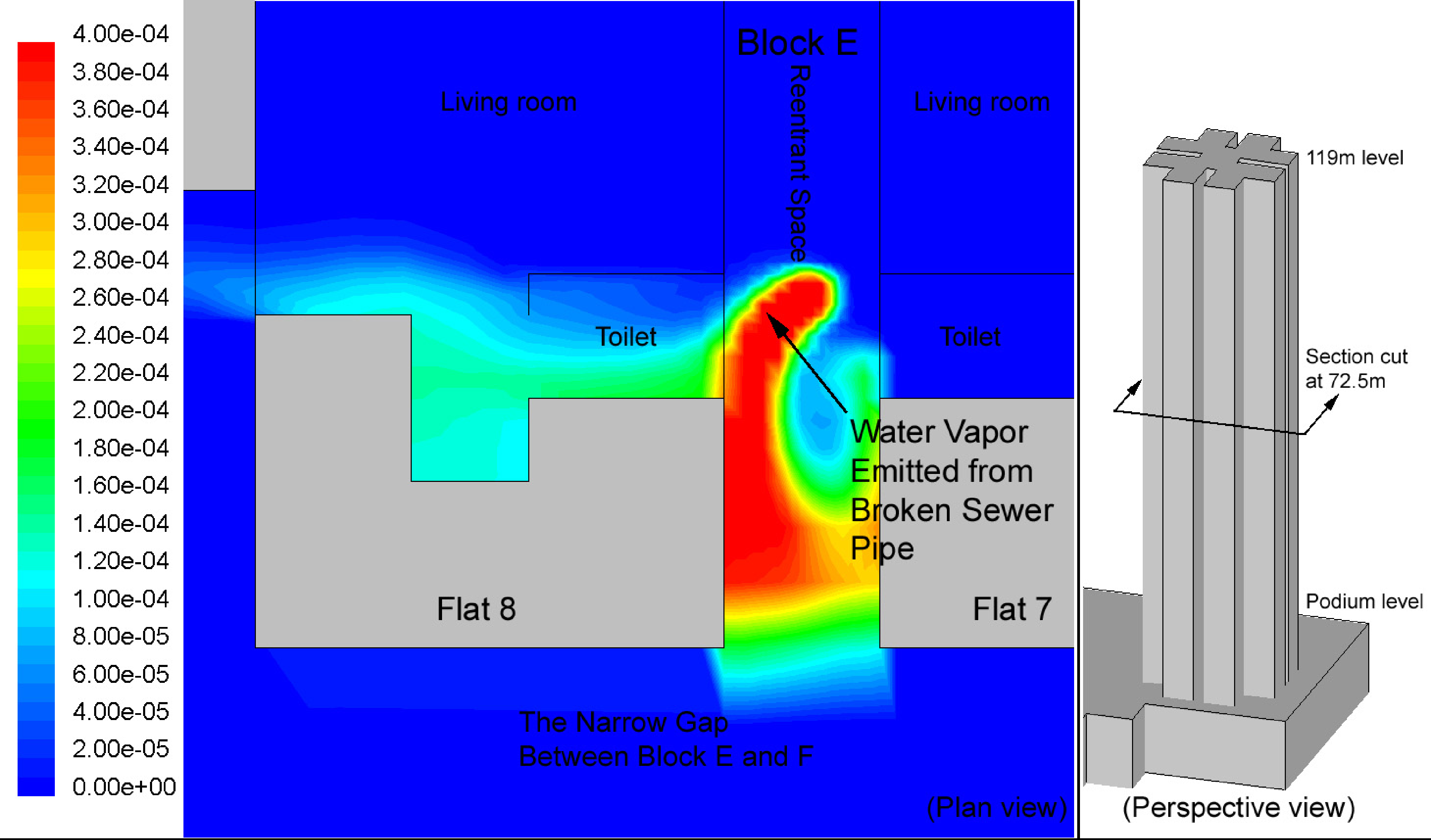
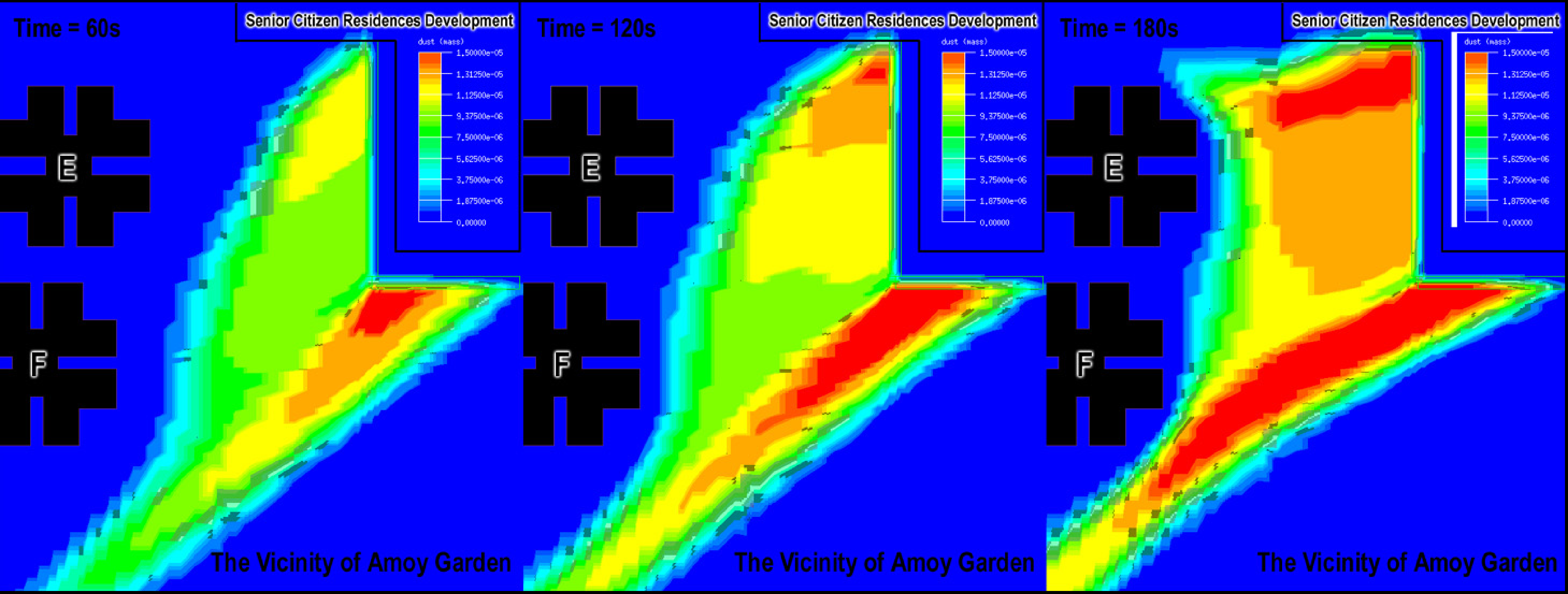


Figure 13: Flow of Water Vapor and Bathroom Exhaust into Adjacent Flats
(Contours of mass fraction of water vapor)



After 60s

After 120s

After 180s

Figure 14: Flow of Airborne Particulates into Flats
(Time Dependent Simulation, Contours of Mass Fraction of Particulates)

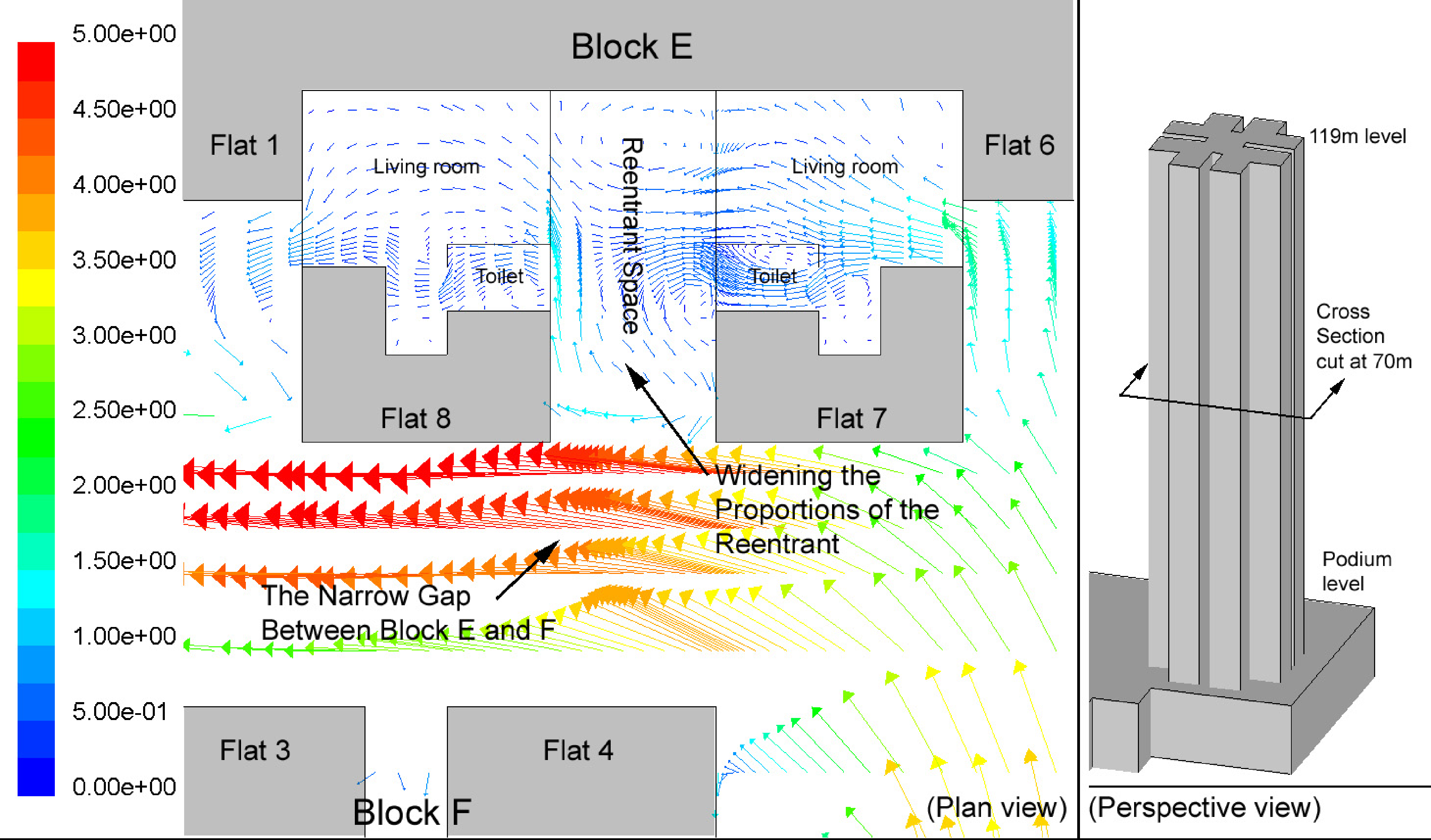


Figure 15: Reduced Concentration of Water Vapor and Improved Ventilation by Increasing the Distance Between Windows and Widening the Proportions of the Reentrant Space. (Velocity magnitude (m/s), clip to 5m/s)

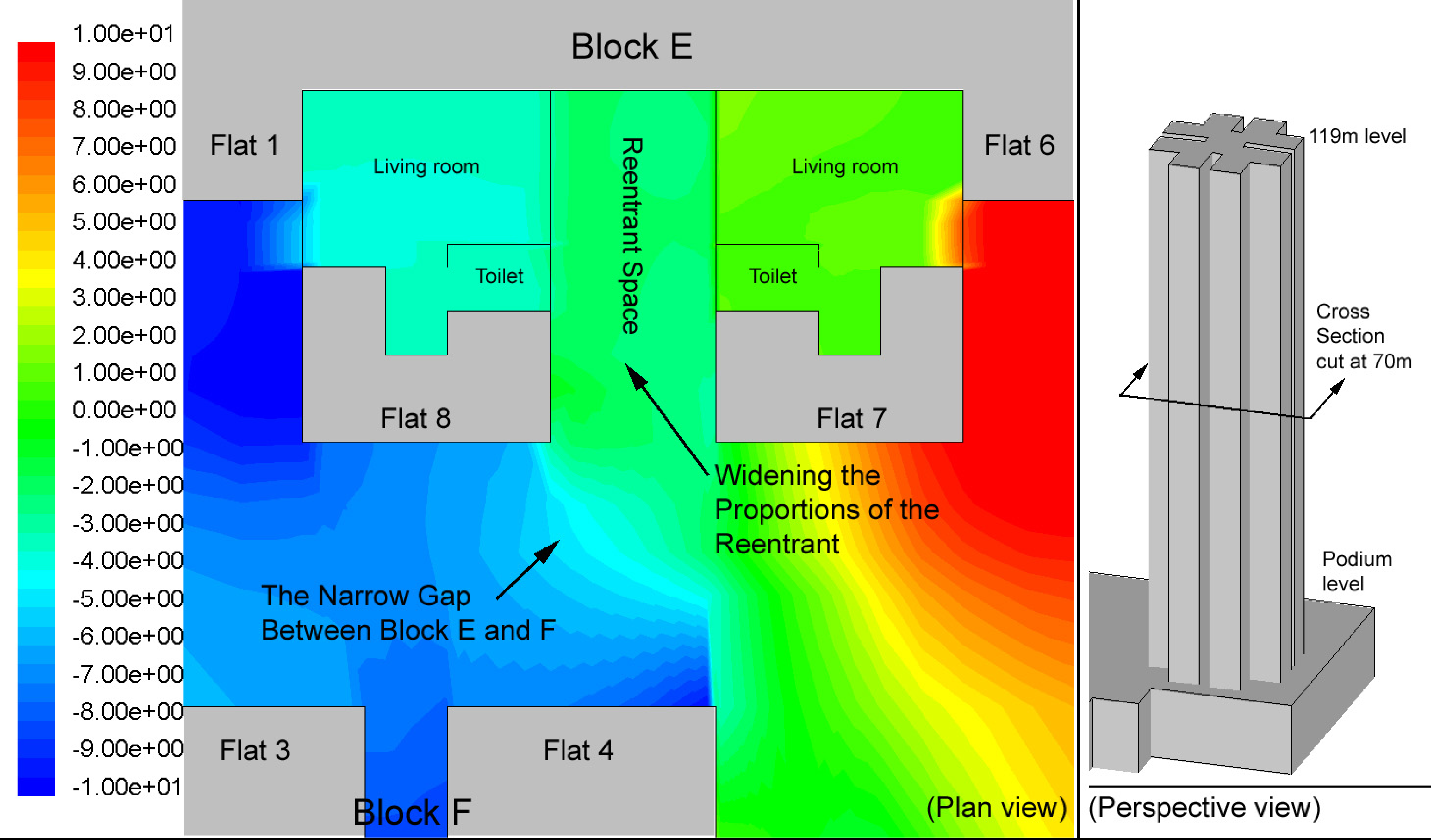


Figure 16: Reduced Concentration of Water Vapor and Improved Ventilation by Increasing the Distance Between Windows and Widening the Proportions of the Reentrant Space. (Static pressure (pascal), clip to -10Pa to +10Pa)

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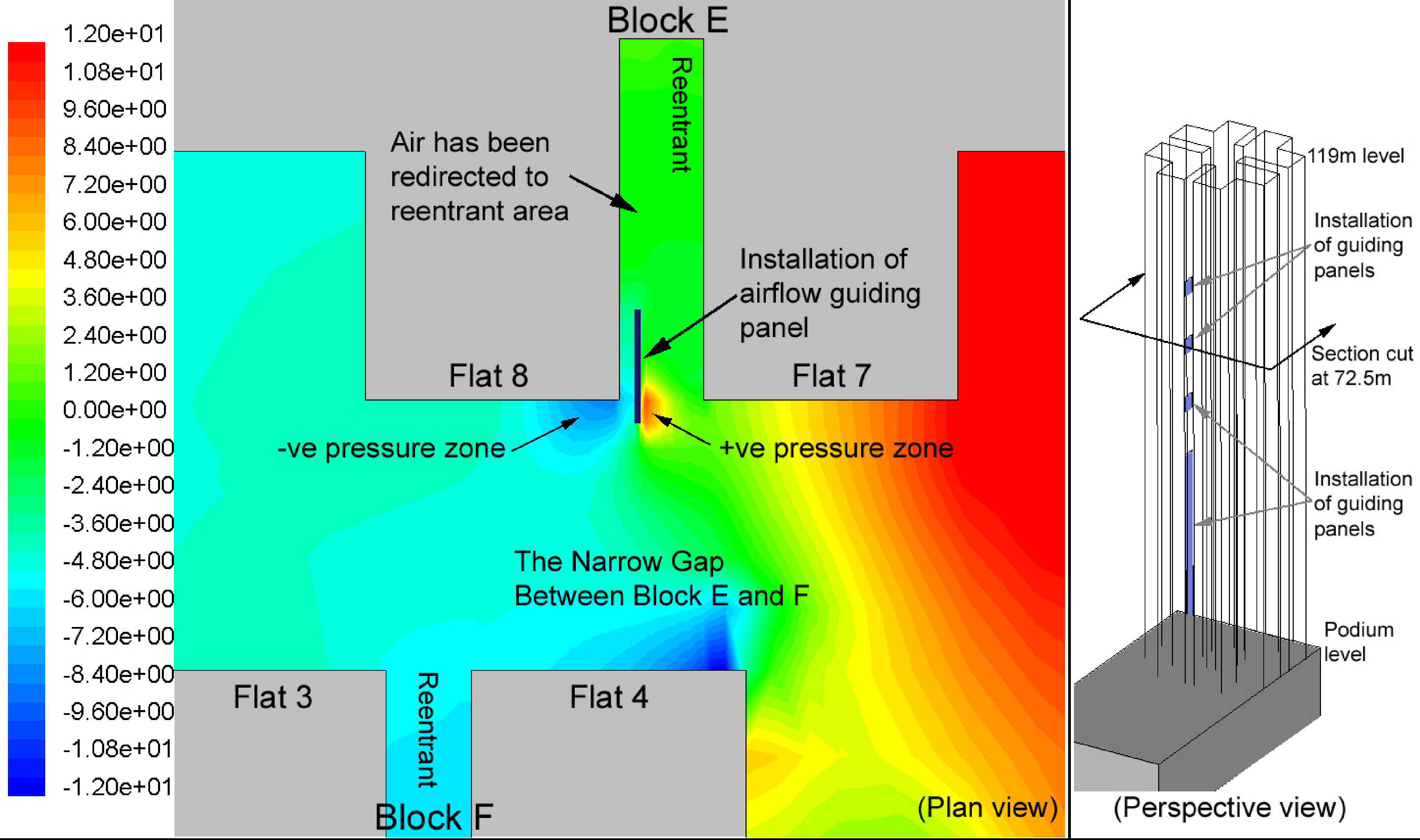

Figure 17: Improved Ventilation of Reentrant Space by Means of an Airflow Guiding Panel
(Contours of Static Pressure in Pascal, Clip to -12Pa to +12Pa)

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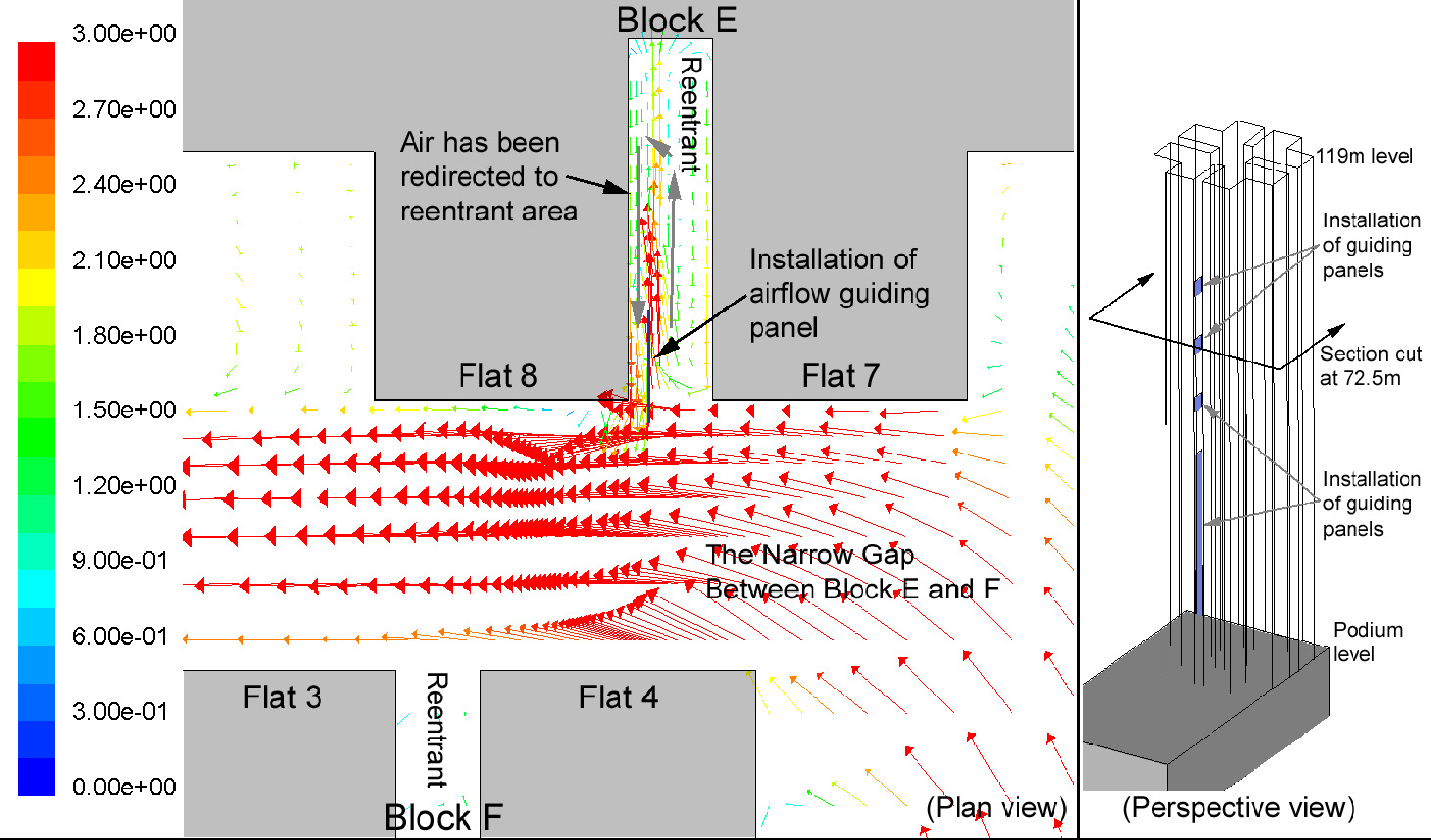

(Plan view)

(Perspective view)

Figure 18: Improved Ventilation of Reentrant Space by Means of an Airflow Guiding Panel (Velocity vectors colored by velocity magnitude (m/s), clip to 3m/s)

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