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Clean Unit System Platform (CUSP) for various frontier experiments and applications

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Abstract*— A clean unit system platform (CUSP), i.e., a system having fan-filter-unit with 100% feedback, is shown to be versatile. Desk-top type CUSPs, Mobile CUSP, room-type CUSP in which people can stay doing processes, and tent-type CUSP are now available. Cleanliness of US 209D class 1 (ISO class 3) can be realized in an inexpensive compact manner with CUSP, no matter how dusty its ambient is. In terms of small footprint, low power-consumption and high cost-performance, CUSP in its full line-up could outperform a conventional super cleanroom, i.e., the "main frame," and will be the *clean space for all of us.

***Index Terms*—Clean room, clean space, particle count, CUSP.**

I. Introduction

In near future, clean environment [1],[2] would surely be necessary to perform cross-disciplinary experiments, especially uniting or unifying bottom-up systems with top-down systems [3]-[5] through the fusion of cutting-edge research technologies such as semiconductor-based nanotechnologies and bio-technologies in addition to flexible assembly processes.

A clean versatile environment having small footprint, low power-consumption and high cost-performance has been needed for the next generation production system as well as for cross-disciplinary experiments. In this context, physics of enabling highly clean environment in less expensive, compact manner is getting of much importance, for many of tools and processes to be used have already been established in being compact.

Clean unit system platform (CUSP) having fan-filter unit (FFU) operate in 100% feedback configuration or closed loop design in an air-tight space, can take a form not only of compact multiply connected clean boxes but also as a hand-carry clean box, desk-top compact box, tent-type clean space, a room, or even a full building. CUSP serves as a clean versatile environment having low power-consumption and high cost-performance, and is suitable not only for processing the next generation new devices [6],[7], but also for cross-disciplinary fields, including medical/hygienic applications. Processes and analyses can be performed in CUSP as extensively as in high performance cleanrooms, much in an inexpensive manner, just like well-designed connected workstations and/or PCs can sometimes outperform expensive mainframe computers.

II. Experimental Results and Discussion

Figure 1(a) shows how a conventional clean room or a clean booth works. In the conventional system, fan-filter-unit (FFU) on the ceiling inhales the ambient air, filtrates it, and pushes it into the main chamber of the cleanroom, where the filtrated clean air dilutes the dusty air inside. Thus the air inside becomes cleaner than that outside. The air inside, which, being subject to activities done by users, gets some dusts out of them, then goes out of the chamber/room, and the cleanliness is maintained in the cleanroom. Thus, the conventional cleanroom is open system in that ambient air comes in and inside air goes out to merge with the ambient air eventually. We note that in the conventional cleanrooms the cleanliness is achieved only indirectly or *passively* by diluting the dusty inside air by filtrated clean air (as shown in Fig. 1(a), the FFU, just filtrating the ambient air, never collects the particles in the chamber). The particles, dusts and/or microbes, go outside, being contained in the outgoing air (thus, depending on what are contained, there could be a risk that people who inhale the air may suffer from them). Further, the conventional cleanroom's FFU, put at the

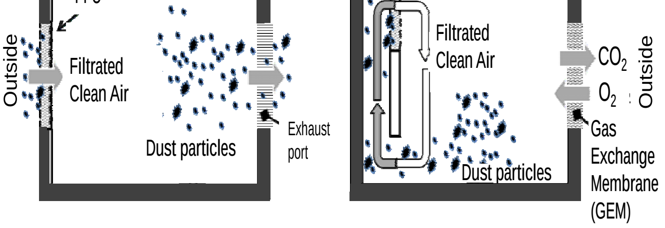

Fig. 1 (a) Conventional system (left) and (b) CUSP (right).

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interface between the ambient and cleanroom, keeps on clogging filtrating the ambient air, which, of course, is infinite in its volume, until it looses its filtrating ability because of the eventual heavy clogging.

On the other hand, in CUSP, as shown in Fig. 1(b), all of the air coming in (to the main chamber) from the outlet of the FFU go back to the inlet of the FFU, i.e., 100% feed-back is done. Thus, the key point of the CUSP is the closed loop, or close circuit design. The CUSP's FFU inhales the return air coming through its inlet, filtrates it and then push it back into the main chamber of the CUSP. Note that in this system the FFU is detached from the ambient air, and so is the main chamber of the CUSP. Thus, the CUSP is closed (isolated) system in that there is no net air-flow exchanged between inside and outside of the CUSP. The ambient air *never* goes into CUSP as a net air-flow. In CUSP, the cleanliness is achieved directly or *actively* by collecting particles (dusts and/or microbes) inside. We call the FFU in CUSP as *active* filter system [8]. The particles generated in the chamber/room in this system never go outside (therefore, there is least risk that people outside might suffer from those particles, even if those particles are toxic or made of harmful microbes). The CUSP's FFU, detached from the ambient air, stops clogging in a finite (actually very short) time of period when cleanliness is achieved, with the inner air having run though the FFU roughly 10 times (thus, in a couple of minutes or tens of minutes, depending on the flow rate *F* of the FFU and the volume *V* of the chamber). In a CUSP for people to work or stay inside, a part of the wall is made of a gas-exchange membrane (GEM), through which gas molecules diffuse if there exists concentration gradient across the membrane. Thus, if oxygen concentration becomes low due to O_2 consumption inside CUSP, the oxygen is fed in through GEM from outside.

Let us consider how the conventional system shown in Fig. 1(a) works. The particle (dust) density $n(t)$ in the chamber, i.e. clean room or clean box, changes governed by the equation,

$$V\frac{dn(t)}{dt} = S\sigma - n(t)F + N_o F(1-\gamma) \qquad (1)$$

where V and S, σ, and N_0 are, respectively, the volume of the chamber, area of the inner surface of the chamber, rate of particles coming from the unit area per unit time, and the particle density of the environment where the conventional clean room itself is placed. F is the flow rate of the HEPA/ULPA fan filter unit, and γ is the filtrating efficiency of the FFU. Equation (1) can be solved exactly quite easily [4] but what we are interested in is the steady-state particle count, n, being obtained just by putting LHS of Eq. (1) i.e., $dn/dt = 0$, and it is given by

$$n = \frac{S\sigma}{F} + (1-\gamma)N_o, \qquad (2)$$

which tells us that $n(t)$ is dependent on the ambient dust density N_0 forever, and that high performance filter with γ very close to one is indispensable in the conventional clean room.

In the case of Fig. 1(b), however, we have the equation:

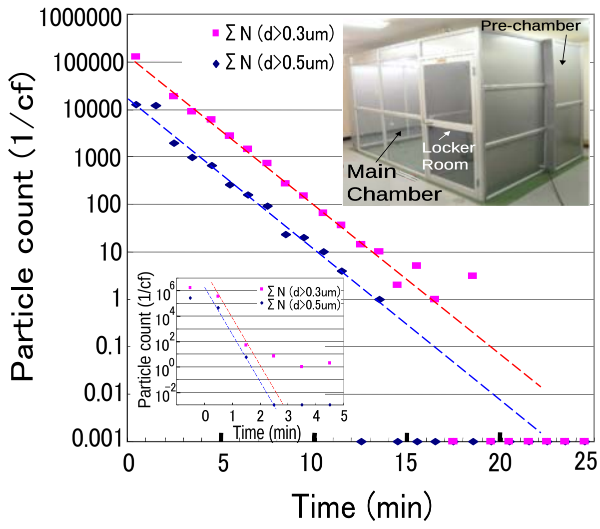

Fig. 2 Particle count as function of time in main chamber of L-CUSP. Upper inset shows the picture of L-CUSP and the bottom left inset shows the time-dependence of the particle count in the pre-chamber of the

$$V\frac{dn(t)}{dt} = S\sigma - n(t)F + n(t)F(1-\gamma) \qquad (3)$$
$$= S\sigma - \gamma F n(t).$$

The solution is:

$$n(t) = \frac{S\sigma}{\gamma F} + [N_o - \frac{S\sigma}{\gamma F}]e^{-\frac{\gamma F}{V}t}, \qquad (4)$$

which is obtained with the boundary condition $n(0)= N_o$. Again we are interested in the steady-state particle count, which is given by

$$n = \frac{S\sigma}{\gamma F}. \qquad (5)$$

This is the steady state dust density obtained as time goes by in CUSP. As seen in Eq. 4, the cleanliness in CUSP chamber is indeed dependent on the ambient dust density at $t \sim 0$, but soon at a time when $t/(V/F) \sim 10$ or later, the cleanliness in the

CUSP chamber becomes independent of the ambient dust density N_o, and is given by Eq. 5. As Eqs. 2 and 5 teach us, in conventional system, γ being as close to unity as possible (γ=0.997 for HEPA, or γ=0.99997 for ULPA) is important but in CUSP γ close to 1 is not so much indispensable ($\gamma \sim 0.95$ can give class 10~100 as we see below).

Figure 2 shows the time dependence of the airborne particle count in the Lung-CUSP (L-CUSP), i.e., a CUSP that

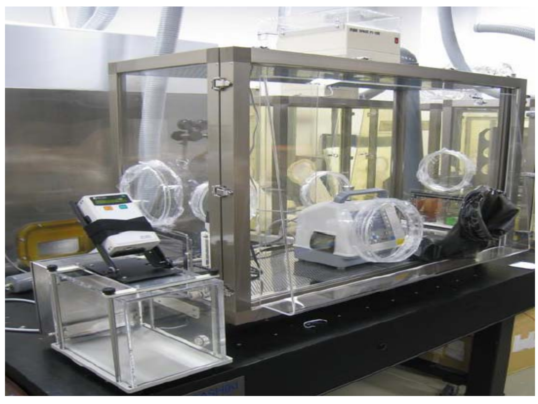

Fig. 3 Mobile CUSP (left) and a desk top CUSP (right).

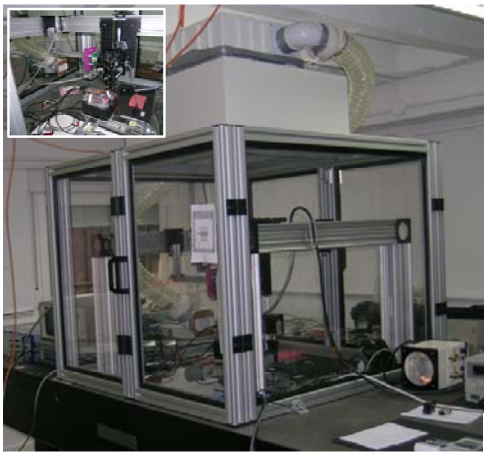

Fig. 4 Desk-top CUSP for optical experiments. The inset shows the nanophotonic experimental setup.

has GEM as shown in Fig. 1, and people stay long inside by exploiting its lung-like feature. The top inset of Fig. 2 is a picture of the L-CUSP whose size is roughly 3m long, 2m wide, and 2.3m high. The solid square shows the number, per cubic feet, of particles whose size is 0.3μm or larger and the solid diamond that 0.5μm or larger. Measured zero counts are plotted at n=0.001 for simplicity to avoid infinity. As seen from Fig. 2, the cleanliness inside becomes as good as US FED 209D class 1 (= ISO class 3) in about 20 minutes. The L-CUSP is equipped with a pre-chamber that also has the CUSP 100% feed-back system which also serves as air shower. The cleanliness in the pre-chamber reaches at US 209D class 1 quickly in two minutes. Thanks to the pre-chamber, we can go into the main chamber without breaking the high cleanliness of it.

As seen from Eqs. 4 and 5, CUSP is scalable and we can make hand-carry CUSP (left-hand side) or mobile CUSP (M-CUSP) and a desk-top CUSP (right-hand side) as shown in Fig. 3, both of which enables high cleanliness [9]-[13]. M-CUSP, with a size is 23 cm × 30cm × 35 cm, working 10 hours with four AA batteries connects any two clean facilities. Desktop CUSP can be used not only as clean version of a glove box, but also for optical and nanophotonic experimental platforms. Figure 4 shows the system that maintains a total volume of about 1 m^3 used for the characterization of nanophotonic devices. In this application, dust can affect the amount of light directed towards the workplane due to scattering on the mirrors and optical

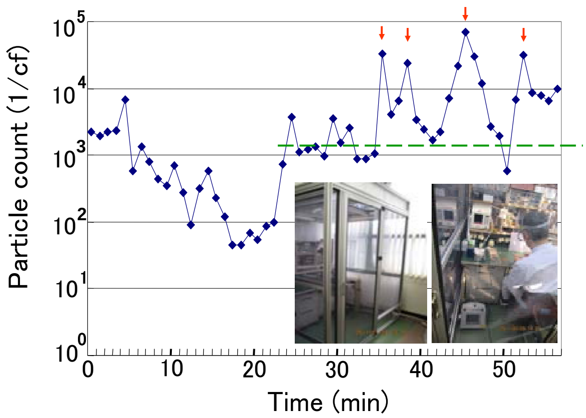

Fig. 5 Particle counts under the dental processes in DSS. The left inset shows the outlook of DSS, and the right one the dental work being performed inside.

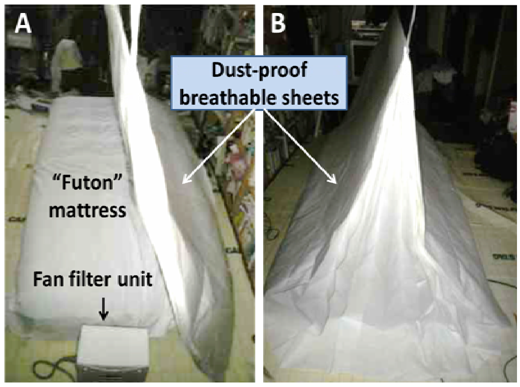

Fig. 6 A tent-type CUSP (T-CUSP): a) when out of use, and b) when in use.

surfaces. Besides, when working with high power laser, dust may burn and degrade optical surfaces. Nanophotonic elements exposed to the ambient air can be damaged with dust particles that are deposited and fixed electrostatically at those locations where electric fields are enhanced. Then, CUSP reduces the maintenance stops of the experimental equipment and preserves samples and devices longer.

The CUSP system with GEM can be used for a dental technician to perform dental work as shown in the right inset of Fig. 5. We call this set-up a dental safety system (DSS), whose outlook is shown in the left inset of Fig. 5. We have investigated how particle count changes when various dental technological processes are done in DSS. Figure 5 shows the particle counts: first, for a couple of tens of minutes, metal polishing is performed, but as shown in Fig. 5, the particle count goes down and the cleanliness is as good as class 100 (ISO class 5) even when the metal polishing is done inside. Then, after 20 minutes, process is switched to polishing with abrasives, and red arrows in Fig. 5 denotes the timing when a blower is used, for which the particle count increases, but the cleanliness is class 10000~100000 (ISO class 7~9), a typical cleanliness for offices, which demonstrates very high performance of DSS to keep the dust count moderate even if there is much dust generation inside. DSS will serve as a good platform for dental processes making it possible to protect dental technicians from heavy dust generations.

Japan has a long tradition of "*Kaya*" a net to prevent mosquitos from getting close while people are sleeping especially for summer. We have expanded the concept of *Kaya* by replacing the target, i.e., mosquitos by particles/dusts, and developed the tent type CUSP (T-CUSP) as shown in Fig. 6. People can sleep inside T-CUSP as usual with futon or mattress as shown in the left picture of Fig. 6.

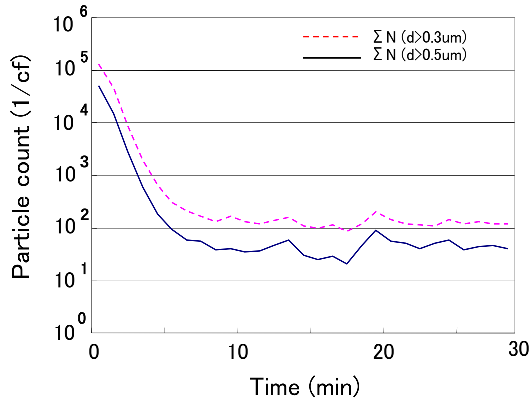

Fig. 7 Time-dependence of particles count in T-CUSP.

The T-CUSP size is compact, i.e., just enough to cover futon/mattress, which makes the volume of T-CUSP small and, as predicted from Eq. 4, low particle state is established quickly. The flow rate of FFU used in T-CUSP is about 1 cubic meter per minute. The cleanliness provided is shown in Fig. 7. The solid line shows the number per cubic feet of particles whose size is 0.5 um or larger. The cleanliness reaches class 100 in 5 minutes. Note that super cleanrooms have been used almost exclusively for semiconductor device processing, and it would be ridiculous to even try to sleep in super cleanroom with ordinary bedclothes. With T-CUSP, however, it has become quite affordable to sleep in clean-space. Users can enjoy non-invasive, non-contact natural sleeping [14] in clean air, being free from nuisance of using a mask, under lower risk of suffering from PM2.5 [15],[16] and/or diseases mediated by airborne microbes.

CUSP system could even scaled up to various size of rooms as shown in Fig. 8 and 9. The room shown in Fig. 8 is about 70 m^3, and that in Fig. 9 is with a volume of 800 m^3. CUSP FFU flow rate is 16.7 m^3/min for the medium-sized room and the cleanliness achieved is roughly class 1000 (ISO class 6). For the large-sized room, the flow rate of CUSP FFU is 70 m^3/min and the cleanliness achieved is about class 5000. Those results are in good accord with the scaling property predicted by Eqs. 4 and 5.

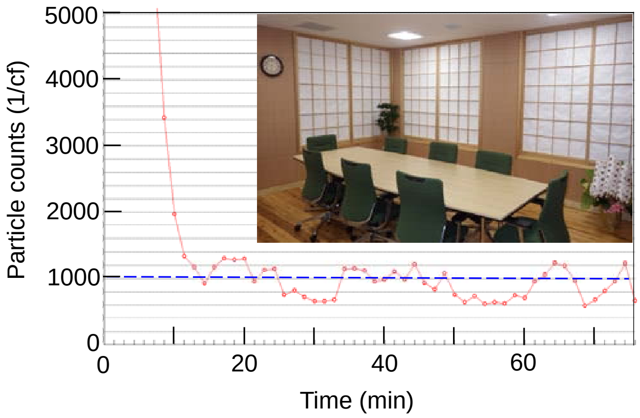

Fig. 8 Particle count as function of time in a medium-sized room-type CUSP. The inset is a picture of the room having GEMs.

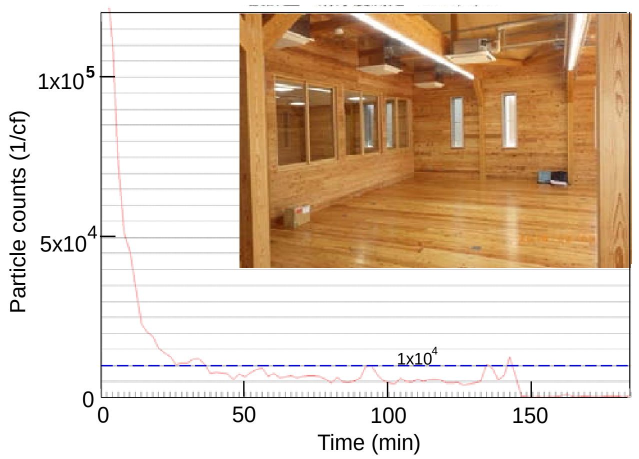

Fig. 9 Particle count as function of time in a large-sized room-type CUSP. The inset is a picture of the room before furniture is brought in.

III. Conclusions

Clean versatile environments having small footprint, low power-consumption and high cost-performance can be realized with clean unit system platforms (CUSPs) for the next generation production system as well as for cross-disciplinary experiments. By feeding back the outlet air into the inlet of the CUSP unit, the steady-state airborne-particle-count in the system becomes independent of the ambient particle count and dependent little on the particle-arrest efficiency of the filter. We can realize the cleanliness of US FED class 1~5000 for various applications. The CUSP being a closed system having no pressure difference between inside and outside, high cleanliness can be achieved with CUSP, no matter how dusty the ambient is. Thus, CUSP can provide us with the high cleanliness, for example, in a laboratory, office or home in inexpensive manner.

Desk-top type CUSPs, Mobile CUSP, and L-CUSP in which people can stay doing processes, foldable tent-type CUSP (T-CUSP), and room-style CUSP are now available. Multiply-connected CUSP system based upon those would serve as the platform not only for nano-technologies or bio-technologies but also for the next-generation environment-friendly platform for industries and medicines, especially family/community medicine. In terms of low power-consumption and high cost-performance, CUSP in its full line-up could outperform a conventional cleanroom ("main frame") and would be *the cleanroom for all of us*.

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