A BIBLIOGRAPHIC SURVEY OF NUMBER OF CELLS NEEDED IN CFD ANALYSIS OF ROOM AIR FLOW

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ABSTRACT

This study prepares a list of articles on the CFD analyses of room air flow in the architecture field in Japan, and compiles information related to CFD analysis conditions described in each article. The discussion addresses trends in analytical conditions in Japan, the yearly transition of the number of cells, usefulness of the estimate formula for the number of cells of VDI 6019, and a rough guideline for number of cells for a low Reynolds Number model.

INTRODUCTION

It is necessary to set up various analysis conditions properly to obtain reliable results from CFD analysis. Most important requirements include partitioning of an analysis grid, such as the number and width of cells. Practical CFD analyses adopt an analysis grid according to a problem considering the computation time and capacity. Therefore, the number of cells is important information to secure analytic accuracy.

An analysis grid suitable for each problem shall be adopted according to the delivery period or prescribed precision, in CFD analyses for practical use, such as air conditioning design. Because analysis of grid partitioning strongly depends on experience, it is desirable that guidelines for the number of analysis grids, etc. be specified for an air conditioning engineer with poor experience. It is also necessary to examine the validity of an analysis grid from a viewpoint of quality assurance.

The Association of German Engineers proposes a rough formula for estimating a room volume and the number of cells as the standard VDI 6019 (dimensioning of systems for the removal of smoke), which is introduced into the REHVA guidebooks, for example. This estimated formula is a guideline for the analysis of the removal of smoke using the standard k-ε model. However, its validity for the analyses of other closed spaces, such as office rooms, has not been fully confirmed. Moreover, no guideline has been prepared for a low Reynolds number model, which is increasingly applied recently to computation.

The CFD analysis has been studied in the architecture and air conditioning fields in Japan since 1972(Kaizuka et al.), with over 3,000 papers accumulated to date.

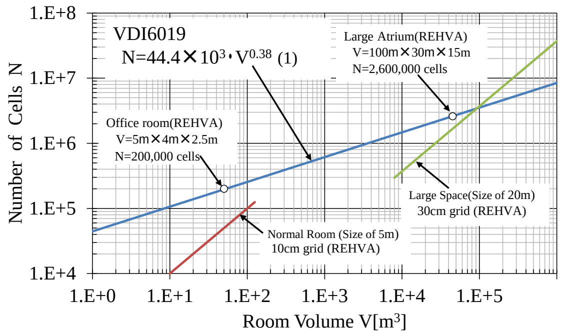


Fig.1 Rough guideline formula on number of cells needed in room air flow (VDI6019)

It is expected that compiling these papers shall provide us with experiential information related to analysis conditions such as grid partitioning. Accordingly, this study prepares the list of papers on the CFD analyses of room air flow in the architecture field in Japan, and compiles information related to CFD analysis conditions described in each paper. We have investigated trends of the analysis conditions in Japan, the yearly transition of the number of cells, usefulness of the estimate formula for the number of cells of VDI 6019 (hereinafter designated as the VDI formula), and a standard for cell partition for the low-Re model. This paper reports the results.

REVIEW OF VDI FORMULA

VDI 6019 proposes the following formula (1) as a part of a CFD analysis guideline for dimensioning of systems for the removal of smoke.

$$N_{VDI} = 44.4 \times 10^3 \times V^{0.38} \tag{1}$$

Therein, N_{VDI} stands for the number of cells required for CFD analysis; V represents the room volume [m^3]. This formula provides a rough estimate for the standard k-ε analysis. The partitioning of a boundary layer is out of scope. Details of derivation are not described in references and remain unknown. Related references carry recommended values for the grid expansion ratio to be about 1.5 or fewer and the grid orthogonality required, and the description example of analysis conditions for quality assurance in addition. The REHVA guidebooks also present guidelines and an example of a general grid width. Figure 1 shows VDI 6019 with the general guideline of REHVA appended.

OUTLINE OF LITERATURE SEARCH

Scholarly and Academic Information Navigator (CiNii), a science and technology article search services in Japan, and the proceedings of the annual meeting of the Society of Heating, Air-conditioning & Sanitary Engineers of Japan (2001–13) were used for the collection of papers on CFD. Author names related to the CFD were used as keys to search by CiNii. Consequently, a total of 2,530 papers were collected (e.g. Murakami, 1987,1991) .

Out of the papers collected, the following four categories of basic information were extracted: (1) title, (2) author name(s), (3) journal title, and (4) year of publication, and furthermore, the following seven items were extracted as analysis information: (5) room volume, (6) the number of cells, (7) turbulence model, (8) analysis code, (9) the scheme of convective term, (10) algorithms, and (11) boundary condition. In addition, (12) usage of object space was extracted from papers that included information (5), (6), and (7), and in the case of the low Reynolds number(LRN) k-ε model, (13) description on y+ and (14) the first cell size were also extracted.

SURVEY RESULTS

Trend of analysis conditions in Japan

Figure 2 presents the transition of the number of published papers on the CFD by year. Papers on the CFD were first published in 1972. The number of publications started increasing since the latter half of the 1980s. The number is increasing further since the latter half of the 1990s. A decline after 2010 is considered because of a time lag until new articles being appended to the databases.

Figure 3 presents the ratio of description of each analysis condition on the CFD papers. As a whole, items like the analysis volume, the number of cells, the turbulence model, and the boundary conditions are described in not less than 60% of the articles. The turbulence model is most described, in 75%, whereas the analysis code and the CFD algorithm are less described, in about 25%.

The application state of the analysis code is portrayed in Fig. 4. STREAM, a code for structural grid, is outstanding in the air conditioning field in Japan with subsequent STAR-CD and FLUENT.

Figure 5 depicts the application state of the CFD algorithm, in which SIMPLE outperforms others.

The application state of the convective term difference scheme is depicted in Fig. 6, which suggests that QUICK and the first upwind scheme prevail. It is also revealed that PLDS is used only for the convective term difference of a scalar equation. The present survey found few application examples of the TVD scheme except MARS.

Turbulence models applied to the CFD are presented in Table 1, in which the number of papers represents that of articles describing the analysis volume,

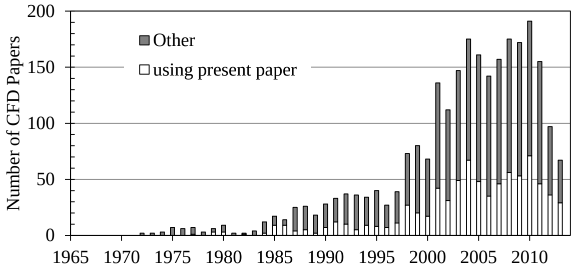


Fig.2 CFD paper with changes of the years in Japan

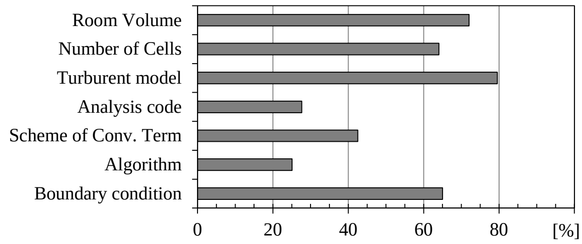


Fig.3 Listed rates of Simulation condition

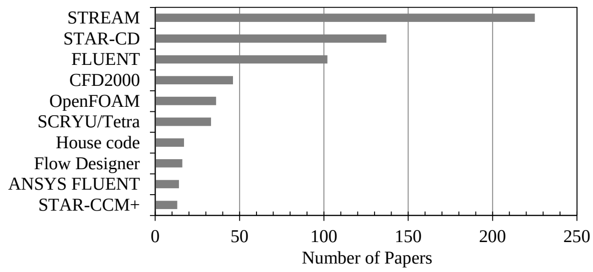


Fig.4 Number of papers according to CFD code

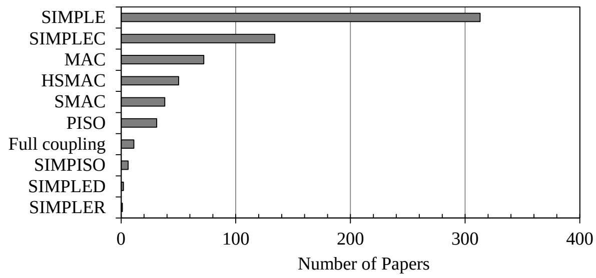


Fig.5 Number of papers according to Algorithm

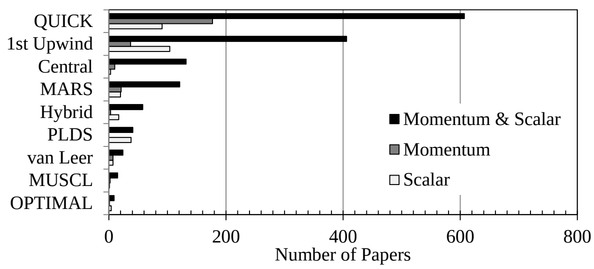


Fig.6 Number of papers according to scheme

Table 1 Number of papers according to Turbulence model using present paper

Standard k-ε	749
Low Reynolds Number k-ε	244
LES	62
other	44

Table 2 Analysis condition of LRN k-e

Mention of y^+：97. Mention of cell size attached wall：26.
Cell size attached wall : average 0.64, min. 0.005, max.3mm.
Mention of expansion rate of cell near wall：4
Mention of $y^+<n$：n<1:10，n＝1:34，almost n＝1:29，n>1:18

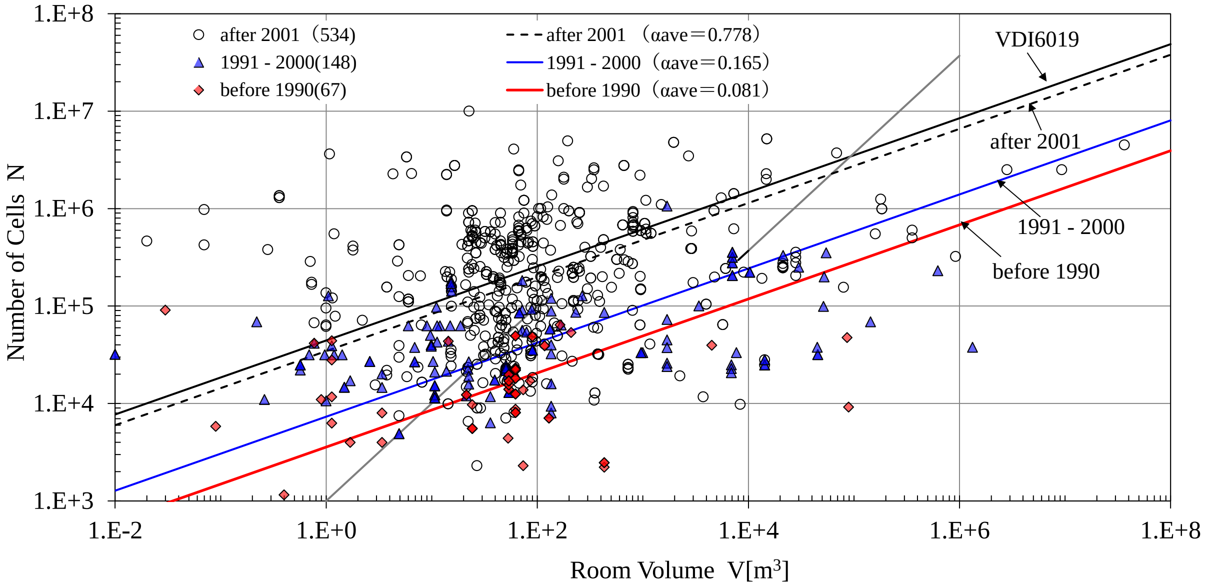


Fig. 7 Relationship between Room volume and Number of cells in Standard k-ε model

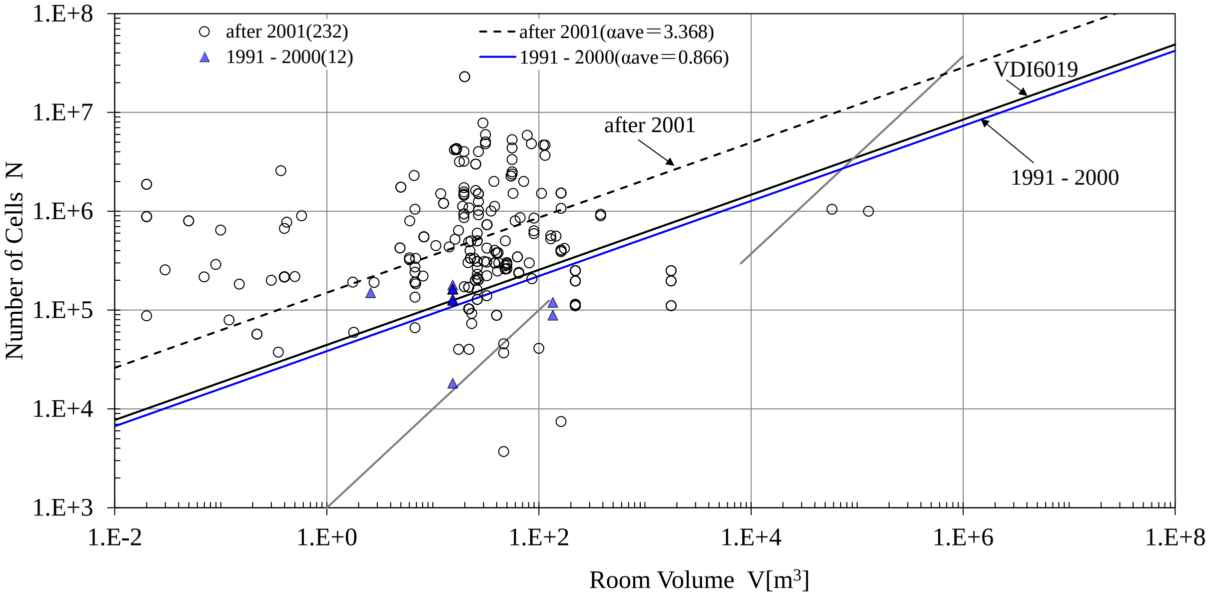


Fig. 8 Relationship between Room volume and Number of cells in Low Reynolds Number k-ε model

the number of analysis grids, and the turbulence model. The standard k-ε model prevails, but the LRN model is increasing since 2000.

Table 2 presents a description on the analysis conditions in the articles that employ the low-Re model. Results show that, out of 244 papers, 97 mention y+ and only 4 mention the expansion rate. It is considered that a guideline on the statement of analysis conditions be prepared in the future, from the viewpoint of quality assurance.

Relation between *V* and *N*

The relation between room volume and the number of cells in real analysis cases are shown in Figs. 7 and 8, which respectively present the results of the standard k-ε model and the low-Re k-ε model. Only papers carrying information (5), (6), and (7) are shown. Regarding problems solved using dimensionless analysis, corresponding physical dimensions are given based on information related to the calculation objects. Data are classified by time period and presented separately as before 1990, 1991–2000, and after 2000. Straight lines in the figures are explained later.

A number of cells N about 0.1–10 times of that given by the VDI formula(N_{VDI}) are adopted for the room volume(V)of 1–1,000 m^3 for the standard k-ε models in Fig. 7. That great deviation is attributed to diverse mesh subdivision according to study objectives. The numbers of cells is distributed at 100,000 or fewer before 1990 and at 400,000 or fewer before 2000, mostly irrespective of a room volume, presumably because limited calculation resources were available for solving various problems those days.

Slight volume dependency is observed since 2000. The maximum number of cells is 10,000,000, a case for plant production facilities (Sawada et al., 2010).

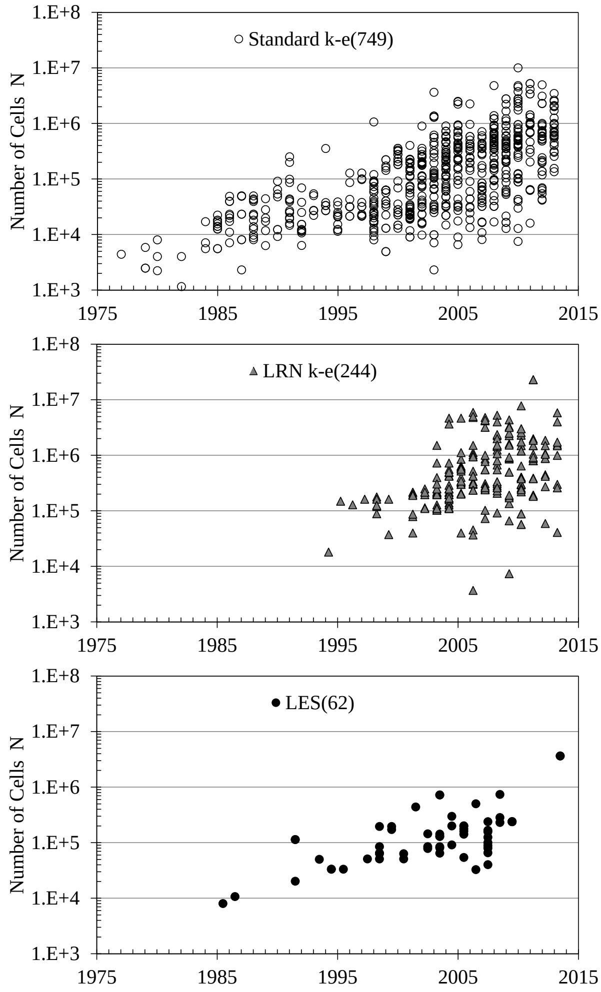


Fig.9 Year change of Number of Cells

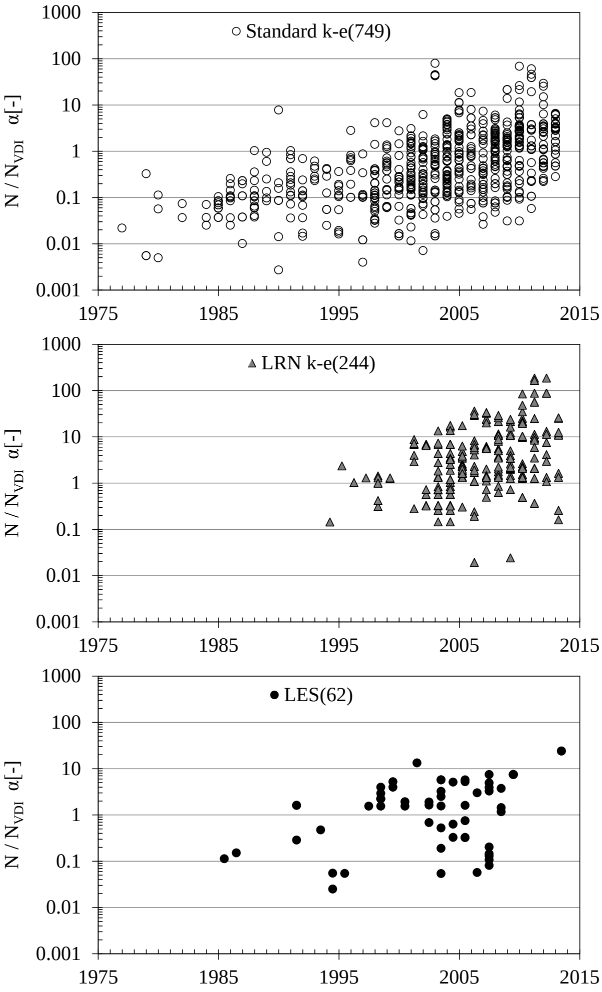


Fig.10 Year change of a

The number of cells is about 0.1–1 times of the VDI estimate for a volume of 10,000 m^3 or above. This suggests insufficient cell partitioning in the analysis of a large space.

The low Reynolds number k-ε models of Fig. 8 mostly employs about 1–10 times of N_{VDI}, presumably because the mesh subdivision is conducted near wall surfaces. The maximum number of cells for the LRN model is 23,000,000, a case for the numerical analysis of a human body including an air space between clothes and the skin (Yube et al., 2011).

Data of Figs. 7 and 8 are distributed unevenly around a room volume of 100 m3; few data are applicable to large spaces, presumably for the following reason: studies assessing populations mostly aim at verification of the precision of the CFD, and carry few data on practical CFD analyses. It is therefore necessary to investigate the actual conditions of companies that practically perform facility design business in the future.

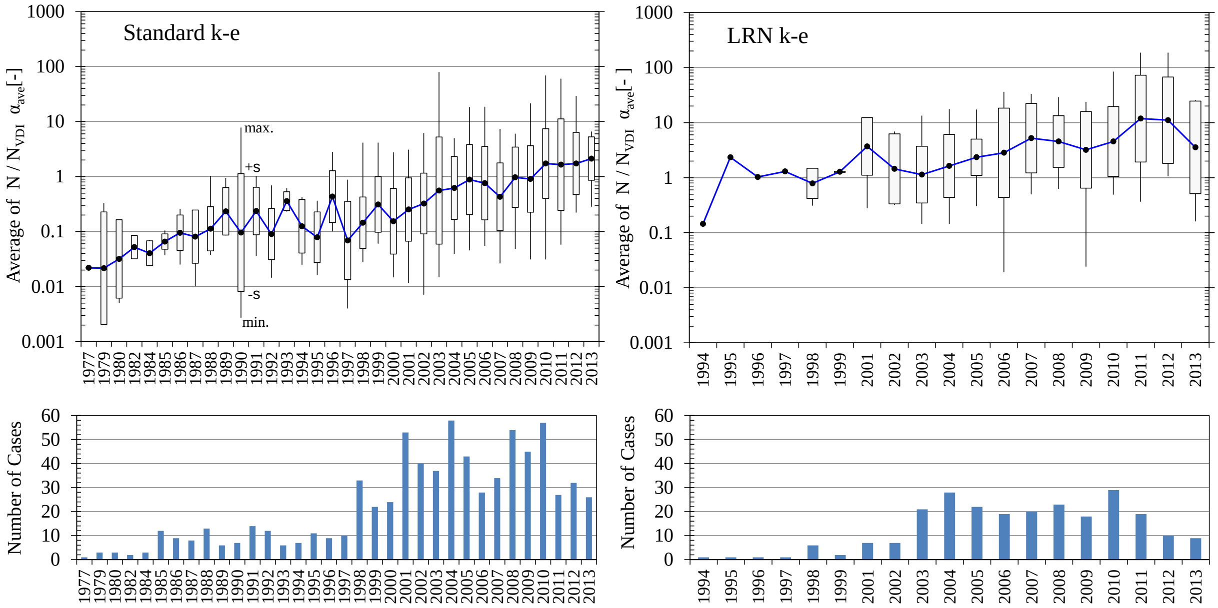
Derivation of the relational expression between cell volume and the number of cells in a real analysis was attempted using data in this study. However, significant variation in the number of cells over years, big deviation at the same volume, and few available data for large spaces, precluded derivation of a statistically dominant estimate formula.

Annual transition of the number of cells

Figure 9 presents the yearly transition of the number of analysis cells for each turbulence model. Articles not carrying information (5), (6), and (7) are excluded. The numbers of cells increase year by year. LRN k-ε models employ slightly more cells than the standard k-ε models, but the number of cells of the LES models was comparable as others. Because it was difficult to derive an estimate formula out of the present data, we decided to respect the VDI formula and to evaluate the number of cells of real analyses by its multiplying factor to a value given by VDI formula in this article.

A volume described in each article was substituted to formula (1); the number of cells required N_{VDI} was determined. Then, the actual number of analysis cells N was divided by N_{VDI}, to determine the multiplying factor α to the VDI formula.

Figure 10 shows the computed results of the multiplying factor α, which scatters centering on about 0.1 before 2000 and 1 after 2000 in the standard k-ε models.



(a) Standard k-e *(b) Low Reynolds Number k-e*

Fig.11 Year change of a_{ave}

Annual deviation is great, ranging about 0.01–100. The multiplying factors for LRN models were several times greater than those for the standard k-ε models, although they were distributed centering on 1 for the LES. REHVA recommends a multiplicative factor of 100 or above of the VDI formula in the LES and 10 or above in the DES. The multiplying factor for the LES is low presumably because the sufficient number of cells was not assured as a result of restrictions of calculation resources.

Average multiplicative factor to the VDI formula

The number of cells N and the multiplying factor to N_{VDI} change greatly every year. Therefore, the average and standard deviation of the multiplying factor α in each year were determined. Averaging is performed using the common logarithm of raw values. Figure 11 indicates the average multiplying factor α_{ave}, the standard deviation σ, the maximum, and the minimum in each year. The α_{ave} increased gradually to more than 1 in 2008 and afterwards for the standard k-ε model, whereas it surpassed 10 in 2011 and 2012 for LRN k-ε model. Straight lines in Figs. 7 and 8 were computed as N_{VDI} multiplied by the average multiplying factor α_{ave} for each time period of before 1990, 1991– 2000, and after 2000. The standard deviation σ and other related values of α_{ave} after 2001 are listed in Tables 3 and 4. Figure 7 depicts the overall average multiplying factor (after 2000) as about 0.78. The population of this study typically conducted analysis with the number of cells comparable as N_{VDI} in spite of a large deviation. The low-Re models among the present population used about 3.4 times N_{VDI}. However this value is not regarded as representing the latter models, because few data have volume over 1,000 m^3 and many data with no analysis conditions described.

The average multiplying factor αave after 2010 was about 1.8 for the standard k-ε models and 7.8 for the low-Re models.

It is desirable to assure the number of cells N about 1–2 times for the standard k - ε models and about 5–10 times LRN models compared with N_{VDI} given the present computing power. Because the average multiplying factor α_{ave} is dependent on computing power, it is expected to increase further in the future.

The multiplying factor α is indicated in Tables 3 and 4 classified for each purpose. The average multiplying factor α_{ave} is great for simulated kitchens and experimental models, but small for simulated office rooms or large spaces. Moreover, it is greater for LRN models compared with the standard k-ε models for the same purpose. This is assumed because simulated kitchens and experimental models tend to adopt locally fine meshes. A small multiplying factor for large spaces is presumably attributable to restrictions in calculation resources, but for simulated office rooms, it is considered that examination in the initial stage of business design requires fine meshes. This population includes many publications by oral presentation without peer review. Because more detailed examinations are conducted for a reviewed article, multiplying factor α was expected to be greater. However, the average multiplying factor α_{ave} was smaller than in cases without a referee.

Consequently, no statistically dominant relation exists between the analyses investigated and the VDI formula because of great deviation. However, the average multiplying factor α_{ave} of the standard k-ε models after 2001 was around 1. N was comparable as N_{VDI}, whereas N_{VDI} exceeds N in a large space.

Table 3 The average of a by the use of room (Standard k-e, after 2001)

	Number of papers	a average	a minimum	a maximum	Standard deviation (-s - +s)
All data (Fig.4)	534	0.778	0.007	79.5	4.862 (0.16 - 3.78)
Peer review paper only	85	0.338	0.007	15.0	4.813 (0.07 - 1.63)
Experimental model	177	0.956	0.015	79.5	4.962 (0.19 - 4.75)
Office room	121	0.535	0.012	21.5	3.864 (0.13 - 2.07)
Living room	73	0.333	0.023	46.2	4.577 (0.07 - 1.52)
Commercial kitchen	67	2.087	0.564	11.4	1.693 (1.23 - 3.53)
Large space room	33	0.151	0.007	3.0	3.724 (0.04 - 0.56)
Hospital	20	1.399	0.192	5.3	3.200 (0.44 - 4.46)

Table 4 The average of a by the use of room (Low Reynolds Number k-e, after 2001)

	Number of papers	a average	a minimum	a maximum	Standard deviation (-s - +s)
All data (Fig.4)	232	3.368	0.019	186.5	4.746 (0.71 - 15.98)
Peer review paper only	52	2.217	0.019	186.5	6.225 (0.36 - 13.80)
Experimental model	119	5.312	0.160	165.9	3.442 (1.54 - 18.28)
Office room	45	1.161	0.019	25.8	5.472 (0.29 - 8.83)
Living room	35	1.465	0.304	11.3	2.067 (0.71 - 3.03)

The number of cells *N* might increase year by year in the future, but it is considered useful that a CFD analyst employs the VDI formula for solving an actual problem as one of the estimates of quality control.

CONCLUSION

This paper has presented discussion of the trend of the CFD analysis conditions in Japan, the yearly transition of the number of cells, usefulness of the estimate formula for the number of cells of VDI 6019, and a standard for cell partition for a LRN model. The obtained results can be summarized as follows.

As for the description of analysis conditions, items like the analysis volume, the number of analysis grids, the turbulence model, and the boundary conditions are described in not less than 60% of the articles, whereas the analysis code and the computational algorithm are less described, in about 25%. y+ and expansion rate are rarely described in low-Re analyses. A guideline on the statement of analysis conditions must be prepared in the future, from a viewpoint of quality assurance.

We have shown the real conditions of the number of cells in Japan, and estimated it by the ratio to the estimate using the formula of VDI6019. Analysis is conducted with the number of cells comparable to that given by the VDI formula in the standard k - ε analysis after 2000, but at a multiplying factor of about 3 in LRN analysis. Moreover, a trend is observed by which the number of cells increases year by year. The examination described above has verified that the VDI formula is useful as one estimate. Future subjects shall include a survey of companies actually performing air conditioning design business operations.

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