Preliminary Analyses on Hydrogen Diffusion through Small Break of Thermo-chemical IS Process Hydrogen Plant

Marketa SOMOLOVA*, Atsuhiko TERADA, Hiroaki TAKEGAMI
and Jin IWATSUKI

IS Process Technology Group
Nuclear Science and Engineering Directorate

December 2008
Japan Atomic Energy Agency
本レポートは発行する成果報告書です。
本報告の入力並びに著作権利用に関するお問い合わせは、下記あてにお問い合わせ下さい。
なお、本報告の全文は日本原子力研究開発機構ホームページ（http://www.jaea.go.jp）より発信されています。

独立行政法人日本原子力研究開発機構　研究技術情報部　研究技術情報課
〒319-1195　茨城県那珂郡東海村白方白根2番地4
電話 029-282-6387, Fax 029-282-5920, E-mail:ird-support@jaea.go.jp

This report is issued irregularly by Japan Atomic Energy Agency
Inquiries about availability and/or copyright of this report should be addressed to
Intellectual Resources Section, Intellectual Resources Department,
Japan Atomic Energy Agency
2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195 Japan
Tel +81-29-282-6387, Fax +81-29-282-5920, E-mail:ird-support@jaea.go.jp

Preliminary Analyses on Hydrogen Diffusion through Small Break of Thermo-chemical IS Process Hydrogen Plant

Marketa SOMOLOVA*, Atsuhiko TERADA, Hiroaki TAKEGAMI and Jin IWATSUKI

Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

(Received January 7, 2008)

Japan Atomic Energy Agency has been conducting a conceptual design study of nuclear hydrogen demonstration plant, that is, a thermo-chemical IS process hydrogen plant coupled with the High temperature Engineering Test Reactor (HTTR-IS), which will be planned to produce a large amount of hydrogen up to 1000m³/h. As part of the conceptual design work of the HTTR-IS system, preliminary analyses on small break of a hydrogen pipeline in the IS process hydrogen plant was carried out as a first step of the safety analyses. This report presents analytical results of hydrogen diffusion behaviors predicted with a CFD code, in which a diffusion model focused on the turbulent Schmidt number was incorporated. By modifying diffusion model, especially a constant accompanying the turbulent Schmidt number in the diffusion term, analytical results was made agreed well with the experimental results.

Keywords: Hydrogen, Diffusion, Small Break, Turbulent Schmidt Number, Analyses

* Nuclear Research Institute Rez plc (JAEA Foreign Researcher Inviting Program)
熱化学法 IS プロセス水素製造プラントにおける小口径破断
による水素拡散予備解析

日本原子力研究開発機構 原子力基礎工学研究部門
核熱応用工学ユニット

Marketa SOMOLOVA*、寺田 敦彦、竹上 弘彰、岩月 仁

(2008年1月7日 受理)

日本原子力研究開発機構では、高温工学試験研究炉（HTTR）に熱化学法 IS プロセス水素製造プラントを組合して最高1000m³の水素を製造する原子力水素実証プラント（HTTR-IS）の概念設計研究を進めている。HTTR-IS の概念設計の一環として、IS プロセスの水素配管の小口径破断の予備解析をおこなった。これは、安全解析評価の第1段階となるもので、本報告では、乱流シュミット数に着目した拡散モデルを CFD コードに組み込んで得られた水素拡散挙動の解析結果について述べる。乱流シュミット数に随伴する定数を修正することにより、解析結果を実験結果とよく一致させることができた。
Contents

1. Introduction .................................................................................................................. 1

2. Analytical model and conditions .................................................................................. 2

3. Results and discussion ................................................................................................. 8

4. Conclusion ................................................................................................................... 10

Acknowledgements ........................................................................................................... 10

References .......................................................................................................................... 10

Appendix: Literature survey ............................................................................................. 31

目次

1. 序 論 .......................................................................................................................... 1

2. 解析モデル及び解析条件 .......................................................................................... 2

3. 解析結果および考察 ................................................................................................. 8

4. 結 論 .......................................................................................................................... 10

謝辞 ................................................................................................................................. 10

参考文献 .......................................................................................................................... 10

付録　文献調査 .............................................................................................................. 31
This is a blank page
1. Introduction

It is universally admitted that hydrogen is one of the best energy media to alleviate the global warming problem, and its demand will increase greatly in the near future. However, there is a problem about how to produce a large amount of the hydrogen economically while reducing CO\textsubscript{2} emission. Hydrogen production with nuclear heat of a high-temperature gas-cooled reactor (HTGR) is one of the solutions.

Japan Atomic Energy Agency has been conducting a conceptual design study of nuclear hydrogen demonstration plant, that is, a thermo-chemical IS process hydrogen plant coupled with the High temperature Engineering Test Reactor (HTTR-IS), which will be planned to produce a large amount of hydrogen up to 1000m\textsuperscript{3}/h [1]. One of the most important safety design issues for an HTGR hydrogen production system is to ensure reactor safety against fire and explosion accidents because a large amount of combustible fluid is dealt with near the reactor in the system. A number of experiments and analyses was made considered hydrogen release and dispersion, fire and explosions. Representative literatures [2-8] are summarized in Appendix.

As part of the conceptual design work of the HTTR-IS system, preliminary analyses on small break of a hydrogen pipeline in the IS process hydrogen plant was carried out as a first step of the safety analyses. The objective of the work described in this report is to confront 2D FLUNENT code and experiments benchmark calculation for the case of hydrogen jet diffusion which may occur during possible hydrogen plant accident. The existing model for the calculation of this case was used and modified (for better accuracy) by changing the constant of turbulent diffusion term including turbulent Schmidt number. This report presents analytical results of hydrogen diffusion behaviors predicted with the CFD code.
2. Analytical model and conditions

The problem considers the calculation of hydrogen jet diffusion that may occur during possible hydrogen plant accident. Figure 2.1 shows the 2D geometry used for the calculation. The computational grid was created in the ANSYS ICEM program and after that the mesh was adapted in FLUNENT 6.3 code using gradient of static pressure (see the Figure 2.2) [9]. Hydrogen jet leaks out from a nozzle with diameter \( d = 12.7 \text{ mm} \) and length \( L_s = 50 \text{ mm} \). Its total pressure is \( 40.1 \text{ MPa} \) and temperature \( 300 \text{ K} \). Hydrogen is dispersed into the space \((D = 2,000 \text{ mm}, L = 10,000 \text{ mm})\) containing air in ambient conditions (total pressure \( 0.1 \text{ MPa} \), temperature \( 300 \text{ K} \)).

For the calculation were used the following governing equations [10].

1. Transport Equations for the Realizable k-ε model

The Reynolds-averaged approach to turbulence modeling requires that the Reynolds stress be appropriately modeled. A common method employs the Boussinesq hypothesis to relate the Reynolds stress to the mean velocity gradients:

\[
- \rho u_i'u_j' = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left( \rho \kappa + \mu_t \frac{\partial u}{\partial x_j} \right) \delta_{ij}
\] (2.1)

The realizable k-ε model is a relatively recent development. The term “realizable” means that the model satisfies certain mathematical constraints on the Reynolds stress, consistent with the physics of turbulent flows. An immediate benefit of the realizable k-ε model is that it more accurately predicts the spreading rate of both planar and round jets. It is also likely to provide superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation.

The modeled transport equations for \( k \) and \( \varepsilon \) in the realizable k-ε model are

\[
\frac{\partial}{\partial t} \left( \rho k \right) + \frac{\partial}{\partial x_j} \left( \rho k u_j \right) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_h - \rho \varepsilon - Y_M + S_k
\] (2.2)

and

\[
\frac{\partial}{\partial t} \left( \rho \varepsilon \right) + \frac{\partial}{\partial x_j} \left( \rho \varepsilon u_j \right) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 \varepsilon S_k - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_1 \varepsilon \frac{\varepsilon}{k} C_3 \varepsilon G_k + S_\varepsilon
\] (2.3)
where

\[ C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = S \frac{k}{\varepsilon}, \quad S = \sqrt{2S_y S_y} \]  \hspace{1cm} (2.4)

The eddy viscosity is computed from

\[ \mu_i = \rho C_\mu \frac{k^2}{\varepsilon} \]  \hspace{1cm} (2.5)

\[ C_\mu = \frac{1}{A_0 + A_s \frac{k U^*}{\varepsilon}} \]  \hspace{1cm} (2.6)

\[ U^* = \sqrt{S_y S_y + \bar{\Omega}_y \bar{\Omega}_y} \]  \hspace{1cm} (2.7)

and

\[ \tilde{\Omega}_y = \bar{\Omega}_y, \quad \bar{\Omega}_y = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_j} - \frac{\partial u_i}{\partial x_i} \right) \]  \hspace{1cm} (2.8)

where \( \bar{\Omega}_y \) is the mean rate-of-rotation tensor viewed in a rotating reference frame with the angular velocity \( \omega_k \). The model constants \( A_0 \) and \( A_s \) are given by

\[ A_0 = 4.04, \quad A_s = \sqrt{6} \cos \phi \]  \hspace{1cm} (2.9)

where

\[ \phi = \frac{1}{3} \cos^{-1}(\sqrt{6}W) \]  \hspace{1cm} (2.10)

\[ W = \frac{S_y S_y S_{ii}}{S^3} \]  \hspace{1cm} (2.11)

\[ \tilde{S} = \sqrt{S_y S_y} \]  \hspace{1cm} (2.12)

\[ S_y = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \]  \hspace{1cm} (2.13)
The model constants are as follows:

\[ C_{1c} = 1.44, C_2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2 \]  \hspace{1cm} (2.14)

\( G_k \) represents the generation of turbulence kinetic energy due to the mean velocity gradients, \( G_b \) is the generation of turbulence kinetic energy due to buoyancy, \( Y_M \) represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, \( C_2 \) and \( C_{1c} \) are constants, \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers for \( K \) and \( \varepsilon \).

The term \( G_k \) is modeled identically for the standard, RNG, and realizable \( k-\varepsilon \) models. From the exact equation for the transport of \( k \), this term may be defined as

\[ G_k = -\rho \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} \]  \hspace{1cm} (2.15)

To evaluate \( G_k \) in a manner consistent with the Boussinesq hypothesis,

\[ G_k = \mu, S^2 \]  \hspace{1cm} (2.16)

Where \( S \) is the modules of the mean rate-of-strain tensor, defined as

\[ S = \sqrt{2S_{ij}S_{ji}} \]  \hspace{1cm} (2.17)

For high-Mach-number flows, compressibility affects turbulence through so-called “dilatation dissipation”, which is normally neglected in the modeling of incompressible flows.

\[ Y_M = 2 \rho \varepsilon M_t^2 \]  \hspace{1cm} (2.18)

where \( M_t \) is the turbulent Mach number, defined as

\[ M_t = \sqrt{\frac{k}{a^2}} \]  \hspace{1cm} (2.19)

where \( a(=\sqrt{\gamma RT}) \) is the speed of sound.
(2) Species transport

\[ \frac{\partial}{\partial t} (\rho Y_i) + \frac{\partial}{\partial x_j} (\rho u_j Y_i) = -\frac{\partial J_{i,j}}{\partial x_j} \tag{2.20} \]

where \( Y_i \) represents the local mass fraction of each species and \( J_i \) is the diffusion flux of species \( i \).

\[ J_{i,j} = -\left( \rho D_{m,i} + \frac{\mu_i}{Sc_i} \right) \frac{\partial Y_i}{\partial x_j} - \frac{D_{T,i}}{T} \frac{\partial T}{\partial x_j}, \quad Sc_i = 0.7 \tag{2.21} \]

where \( Sc_i \) is the effective Schmidt number \cite{11} and \( D_{m,i} \) is the diffusion coefficient in the mixture, and \( D_{T,i} \) is the thermal diffusion coefficient.

\[ D_{T,i} = -2.59 \times 10^{-7} T^{4.659} \frac{M_i^{0.511} X_i}{\sum_{i=1}^{N} M_i^{0.511} X_i} - \frac{Y_i}{\sum_{i=1}^{N} M_i^{0.489} X_i} \tag{2.22} \]

(3) Energy calculation

\[ \frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_j} (u_j (\rho E + p)) = \frac{\partial}{\partial x_j} \left( k_{\text{eff}} \frac{\partial T}{\partial x_j} - \sum_j h_j J_j + u_i (\tau_i)_{\text{eff}} \right) \tag{2.23} \]

\[ E = h - \frac{p}{\rho} + \frac{u_i^2}{2} \tag{2.24} \]

\[ h = \sum_j Y_j h_j \tag{2.25} \]

\[ h_j = \int_{T_{\text{ref}}}^{T} c_{p,j} dT \tag{2.26} \]

\[ k_{\text{eff}} = k + \frac{C_p \mu_i}{Pr_i}, \quad Pr_i = 0.85 \tag{2.27} \]
where $E$ is the total energy, $k_{eff}$ is the effective thermal conductivity, and $(\tau_{ij})_{eff}$ is the deviatoric stress tensor, defined as

$$
(\tau_{ij})_{eff} = \mu_{eff} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij}
$$

(2.28)

(4) Mass conservation equation

$$
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0
$$

(2.29)

(5) Momentum conservation equations

$$
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \right] + \frac{\partial}{\partial x} (\rho u_i u_j)
$$

(2.30)

where $p$ is the static pressure.

Fluid materials – hydrogen, nitrogen, and oxygen – were defined as in Tables 2.1, 2.2 and 2.3 respectively. The air was considered as a mixture of nitrogen and oxygen (nitrogen mass fraction: 0.77 kg.kg$^{-1}$, oxygen mass fraction: 0.23 kg.kg$^{-1}$).

Next material properties were defined as follows:

(6) Density (compressible flow)

For compressible flows, the gas law is as following:

$$
\rho = \frac{p}{RT \sum_i \frac{Y_i}{M_{w,i}}}
$$

(2.31)

where $p$ is the local relative pressure, $R$ is the universal gas constant, $Y_i$ is the mass fraction of species $i$, and $M_{w,i}$ is the molecular weight of species $i$.

(7) Specific heat capacity

Mixture’s specific heat capacity as a mass fraction average of the pure species best capacities:
\[ c_p = \sum_i Y_i c_{p,i} \]  

(2.32)

Pure component’s specific heat capacity is a function of temperature.

(8) Viscosity

\[ \mu = \sum_i \frac{X_i \mu_i}{\sum_j X_j \phi_{ij}} \]  

(2.33)

where

\[ \phi_{ij} = \frac{1 + \left( \frac{\mu_i}{\mu_j} \right)^{1/2} \left( \frac{M_{w,i}}{M_{w,j}} \right)^{1/4}}{8 \left( 1 + \frac{M_{w,i}}{M_{w,j}} \right)^{1/2}} \]  

(2.34)

(9) Thermal conductivity

\[ k = \sum_i \frac{X_i k_i}{\sum_j X_j \phi_{ij}} \]  

(2.35)

where

\[ \phi_{ij} = \frac{1 + \left( \frac{\mu_i}{\mu_j} \right)^{1/2} \left( \frac{M_{w,i}}{M_{w,j}} \right)^{1/4}}{8 \left( 1 + \frac{M_{w,i}}{M_{w,j}} \right)^{1/2}} \]  

(2.36)
3. Results and discussion

A result was created contours of static temperature, pressure, Mach number, turbulent viscosity, and hydrogen concentration (mole fraction). Distributions of each parameter for nozzle pressure 40.1 MPa and for different Schmidt number are shown in Figures 3.1, 3.2, 3.3, 3.4, and 3.5. X – Y plots of hydrogen concentration on the axis in Figure 3.6 came next.

Figure 3.7 and Table 3.1 show the comparison between experimental [10] and calculated values of hydrogen gas concentration. In the experiment, hydrogen was blown from ½ inch nozzle with pressure 40 MPa and for calculation was used a theoretical diffusion equation (see below). The solid line in Figure 3.7 represents experimental results; the dotted and dash lines represent calculated values from FLUENT code with Schmidt number 0.7 and 1.4 respectively. The explosion range for hydrogen is from 4 to 75 vol. %. In this critical area the modified model gave us more accurate data which corresponds better with experimental results (and therefore this model is more reasonable for safety evaluations).

Theoretical diffusion equation

\[
\frac{C_x}{C_0} = 5.3 \times \frac{D}{x} \times \left( \frac{M_{x0}}{M_0} \right)^{1/2} \times \left( \frac{P_0}{P_a} \right)^{1/2}
\]  

(3.1)

Hydrogen concentration:

\[
C_x = \frac{-b + \sqrt{b^2 - 4c}}{2}
\]  

(3.2)

Coefficients:

\[
A = 5.3 \times \frac{D}{x} \times \left( \frac{1}{M_0} \right)^{1/2} \times \left( \frac{P_a}{P_0} \right)^{1/2} \times C_0
\]  

(3.3)

\[
c = -A^2 M_a
\]  

(3.4)

\[
b = A^2 (M_a - M_0)
\]  

(3.5)

where

\[
C_x \quad \text{Hydrogen concentration at the x position}
\]

\[
C_0 \quad \text{Hydrogen concentration at the nozzle position (1.0)}
\]

\[
D \quad \text{Nozzle diameter (0.0127 m)}
\]

\[
M_0 \quad \text{Hydrogen molecular weight at the nozzle position (2.0)}
\]
\(M_a\)  Air average molecular weight (28.966)

\(M_{x0}\)  Hydrogen average molecular weight on the nozzle center axis

\(P_0\)  Static pressure at the nozzle point

\(P_a\)  Ambient pressure (1.10^5 Pa)

\(x\)  Distance from the nozzle
4. Conclusion

The current model was found to be not sufficiently accurate to predict hydrogen jet diffusion and therefore the model was modified by changing the constant of turbulent diffusion term including turbulent Schmidt number. The modified model showed a good agreement with the experimental results at lower hydrogen concentration within the explosion range of hydrogen. This modified model is thought to be applicable to a general in hydrogen plant safety analysis.

Acknowledgements

The author would like to express my gratitude for support and encouragement to Dr. Shusaku Shiozawa and to Dr. Ryutaro Hino for professional suggestions and comments.

References


Table 2.1  Hydrogen properties

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_p$ [J.kg$^{-1}$.K$^{-1}$]</td>
<td>11,220</td>
<td>13,530</td>
<td>14,310</td>
<td>14,480</td>
<td>14,520</td>
<td>14,550</td>
</tr>
<tr>
<td>$\lambda$ [J.m$^{-1}$.K$^{-1}$]</td>
<td>0.0676</td>
<td>0.13</td>
<td>0.181</td>
<td>0.226</td>
<td>0.267</td>
<td>0.358</td>
</tr>
<tr>
<td>$\eta$ [Pa.s]</td>
<td>4.21x10$^{-6}$</td>
<td>6.81x10$^{-6}$</td>
<td>8.96x10$^{-6}$</td>
<td>1.085x10$^{-5}$</td>
<td>1.259x10$^{-5}$</td>
<td>1.656x10$^{-5}$</td>
</tr>
</tbody>
</table>

Table 2.2  Nitrogen properties

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_p$ [J.kg$^{-1}$.K$^{-1}$]</td>
<td>1,071</td>
<td>1,043</td>
<td>1,041</td>
<td>1,044</td>
<td>1,055</td>
<td>1,074</td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>$\lambda$ [J.m$^{-1}$.K$^{-1}$]</td>
<td>0.02598</td>
<td>0.03252</td>
<td>0.03864</td>
<td>0.0441</td>
<td>0.0493</td>
<td></td>
</tr>
<tr>
<td>$\eta$ [Pa.s]</td>
<td>1.787x10$^{-5}$</td>
<td>2.217x10$^{-5}$</td>
<td>2.602x10$^{-5}$</td>
<td>2.955x10$^{-5}$</td>
<td>3.284x10$^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3  Oxygen properties

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_p$ [J.kg$^{-1}$.K$^{-1}$]</td>
<td>953</td>
<td>915</td>
<td>920</td>
<td>942</td>
<td>1,003</td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>140</td>
<td>200</td>
<td>240</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>$\lambda$ [J.m$^{-1}$.K$^{-1}$]</td>
<td>0.0131</td>
<td>0.0184</td>
<td>0.0217</td>
<td>0.0263</td>
<td>0.0341</td>
</tr>
<tr>
<td>$\eta$ [Pa.s]</td>
<td>1.08x10$^{-5}$</td>
<td>1.48x10$^{-5}$</td>
<td>1.73x10$^{-5}$</td>
<td>2.07x10$^{-5}$</td>
<td>2.58x10$^{-5}$</td>
</tr>
</tbody>
</table>
Table 3.1  Hydrogen concentration changes with distance
· experimental and calculated values

<table>
<thead>
<tr>
<th>Distance x [m]</th>
<th>Mole fraction of hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>2.01647</td>
<td>0.932513</td>
</tr>
<tr>
<td>3.02847</td>
<td>0.82413</td>
</tr>
<tr>
<td>4.04047</td>
<td>0.727301</td>
</tr>
<tr>
<td>5.05246</td>
<td>0.646053</td>
</tr>
<tr>
<td>6.06446</td>
<td>0.578877</td>
</tr>
<tr>
<td>7.07646</td>
<td>0.523200</td>
</tr>
<tr>
<td>8.08845</td>
<td>0.476659</td>
</tr>
<tr>
<td>9.10045</td>
<td>0.437352</td>
</tr>
<tr>
<td>10</td>
<td>0.407288</td>
</tr>
</tbody>
</table>
**Figure 2.1** 2D axisymmetric model with boundary condition (orange color)

**Figure 2.2** Adapted mesh
Figure 3.1 Static temperature distribution around nozzle

(a) Turbulent Schmidt number 0.7

(b) Turbulent Schmidt number 1.4
This is a blank page
Figure 3.2  Static pressure distribution around nozzle
Figure 3.3  Mach number distribution around nozzle
This is a blank page
(a) Turbulent Schmidt number 0.7

(b) Turbulent Schmidt number 1.4

Figure 3.4  Turbulent viscosity distribution
Figure 3.5  Hydrogen concentration distribution
This is a blank page
Figure 3.6  X – Y plot of Hydrogen concentration distribution
This is a blank page
Figure 3.7  Experimental and calculated hydrogen concentrations
This is a blank page
Appendix

Literature survey on hydrogen explosion and detonation experiments and analysis

Introduction

Hydrogen is considered as a future fuel for transportation and stationary use and therefore it is worthwhile to investigate whether we can use hydrogen safely. On that ground a number of experiments and analysis was made considered hydrogen release and dispersion, fire and explosions.

In this literature survey, you can find a list of experiments and analysis on hydrogen explosion and detonation.
A. Literature survey on hydrogen explosion and detonation experiments

Dispersion and explosion field tests for 40 MPa pressurized hydrogen [2]

K. Takenoa, K. Okabayashia, A. Kouchia, T. Nonakaa, K. Hashiguchia, K. Chitoseb

aMitsubishi Heavy Industries Ltd., Nagasaki R&D center, Technical Headquarters, 5-717-1 Fukahorimachi, Nagasaki 851-0392, Japan
bMitsubishi Heavy Industries Ltd., Nuclear Energy Systems Headquarters, Minatomirai, Nishi-ku, Yokohama 220-8401, Japan

Objective
The objective of this research is to collect data which can be used for the evaluation of standards for hydrogen refueling stations for fuel cell powered vehicles.

Experiment description and conditions
This experiment concerns about hydrogen high pressure storage (40 MPa) and envisions two cases of accidents: 1) a pinhole in equipment representing continuous leakage at a constant mass flow and 2) a rupture of the piping leading to a major leakage in short period. First, the diffusion test were conducted prior to the explosion tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage opening</td>
<td>d 0.5 – 10 [mm]</td>
</tr>
<tr>
<td>Ignition time (from start of leakage)</td>
<td>t_{ign} 0.5 – 5 [s]</td>
</tr>
<tr>
<td>Tank capacity</td>
<td>25 – 100 [Nm³]</td>
</tr>
<tr>
<td>Tank pressure</td>
<td>p₀ 10 – 40 [MPa]</td>
</tr>
<tr>
<td>Ignition electric spark</td>
<td>20 [mJ]</td>
</tr>
</tbody>
</table>

0.5 – 7.5 m away from the nozzle, 1 m above the ground

Results
The rise of the pressure wave is very rapid in terms of deflagration. Leakage velocity has a great effect on explosiveness. The overpressure larger than 20 kPa was measured at 3.9 m from the ignition point at t_{ign}=2 s. Maximum explosive power is TNT=5 kg (t_{ign}=0.85 s, d=10 mm, p₀=40 MPa).
Experimental study on hydrogen explosions in full-scale hydrogen filling station model [3]

T. Tanaka\textsuperscript{a}, T. Azuma\textsuperscript{a}, J. A. Evans\textsuperscript{b}, P. M. Cronin\textsuperscript{b}, D. M. Johnson\textsuperscript{b}, R. P. Cleaver\textsuperscript{b}
\textsuperscript{a}Engineering Department, Osaka Gas Co., Ltd., 5-11-61, Torishima, Konohana-ku, Osaka 554-0051, Japan
\textsuperscript{b}Advantica Ltd., Ashby Road, Loughborough, Leicestershire LE11 3GR, UK

**Objective**

The objective of this research is to investigate the safety aspects of hydrogen refueling stations to establish a suitable safety zone around a station.

**Experiment description and conditions**

This experimental program consisted of dispersion and explosion experiments in 1) a model chamber and in 2) a model of filling station: a) the storage room and b) the dispenser. In the explosion experiments was studied an overpressure distribution produced by hydrogen explosions.

1) Test chamber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test chamber volume</td>
<td>22 [m(^3)]</td>
</tr>
<tr>
<td>Test chamber dimensions</td>
<td>8.25x3x2.7 [m]</td>
</tr>
<tr>
<td></td>
<td>front face was open (in some tests also the upper half of two long sidewalls)</td>
</tr>
<tr>
<td>Hydrogen concentration</td>
<td>15, 30, 40, 50 [%]</td>
</tr>
<tr>
<td>Ignition electric spark</td>
<td>placed in the center of gas cloud</td>
</tr>
</tbody>
</table>

**Results**

The largest overpressure was measured for hydrogen concentration 30 – 40 % = 9.8 kPa. Safety zone depends on hydrogen concentration (and this depends on the release and ventilation conditions)

2) Model of a hydrogen filling station

a) Storage room
Storage room dimensions 5x6x4 [m] the top 1 m gap between the roof and the walls
Hydrogen concentration 8, 15, 26 [%]
High-pressure cylinders capacity 250 [l]
High-pressure cylinders pressure 40 [MPa]

Results

<table>
<thead>
<tr>
<th>H₂ concentration in room (%)</th>
<th>Maximum overpressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside room</td>
<td>At station boundary</td>
</tr>
<tr>
<td>8</td>
<td>minimal Not detected</td>
</tr>
<tr>
<td>15</td>
<td>0.4 – 1.3 3.1 – 3.4</td>
</tr>
<tr>
<td>26</td>
<td>&gt; 100 28 · 111</td>
</tr>
</tbody>
</table>

b) Dispenser

| Nozzle diameters 8: 1.6: 0.8 [mm] |
| Storage vessel capacity 250 [l]   |
| Storage vessel pressure 40 [MPa]  |
| Ignition electric spark 4 m from a nozzle |

Results

The ignition time has a significant effect on the overpressure and the maximum overpressure was measured for 1.2 s (above 9.8 kPa).

Large-scale hydrogen deflagrations and detonations [4]

M. Groethea, E. Meriloa, J. Coltona, S. Chibab, Y. Satorc, H. Iwabuchi\textsuperscript{c}
\textsuperscript{a}Poulter Laboratory, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA
\textsuperscript{b}SRI-East Asia, SRI International, Parka Side 8F2, Ichibancho, Chiyoda-ku, Tokyo
Objective
These experiments provide data needed to address accident scenarios and to evaluate numerical models (e.g. AutoReaGas code).

1) 300 m³ experiments

Experiment description and conditions

<table>
<thead>
<tr>
<th>Facility volume</th>
<th>V</th>
<th>300  [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinders dimensions</td>
<td>Num.</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>0.46 [m]</td>
</tr>
<tr>
<td></td>
<td>h</td>
<td>3    [m]</td>
</tr>
<tr>
<td></td>
<td>r₁</td>
<td>1.1  [m]</td>
</tr>
<tr>
<td></td>
<td>r₂</td>
<td>1.9  [m]</td>
</tr>
<tr>
<td>Hydrogen concentration</td>
<td></td>
<td>15 – 30 [% vol.]</td>
</tr>
<tr>
<td>Ignition point</td>
<td>bottom centre of the facility</td>
<td></td>
</tr>
<tr>
<td>10 g of C-4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results
Overpressure and heat flux were measured in this experiments at a range of 15.61 m from the ignition point.

2) Tunnel experiments

Experiment description and conditions
The tunnel represents a vehicle tunnel at 1/5 scale. There were performed spark-ignited deflagration tests (with or without ventilation).

| Tunnel length | 78.5  [m] |
| Tunnel cross-sectional area | 3.74 [m²] |
Hydrogen concentration 9.5 – 30 [% vol.]

Hydrogen release 0.1 kg in 20 s and 2.2 kg in 420 s in the centre of tunnel, with (1.6 m³/s) and without forced ventilation

Vehicle model dimensions 940x362x343 [mm]

placed down the center of the tunnel

**Results**

<table>
<thead>
<tr>
<th>Hydrogen concentration (% vol.)</th>
<th>Pressure pulses (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 (0.32 kg)</td>
<td>Not detected</td>
</tr>
<tr>
<td>20 (0.67 kg)</td>
<td>35</td>
</tr>
<tr>
<td>30 (1 kg)</td>
<td>150</td>
</tr>
</tbody>
</table>
B. Literature survey on hydrogen explosion and detonation analyses

Evaluation of safety distances related to unconfined hydrogen explosions [5]

S. B. Dorofeev
FM Global, 1151 Boston-Providence Turnpike, Norwood, MA 02062, USA

Objective
The objective of this study is to develop a simple approximate method for evaluation of blast effects and safety distances for hydrogen explosions.

Analytical model and conditions
The method includes:

- a model for the evaluation of hydrogen flame speeds,
- a model for properties of “the worst case” hydrogen distribution,
- a model for blast parameters,

  Maximal blast overpressure (P) and positive impulse (I) are a function of distance (R) from the blast epicenter.

- a set of blast damage criteria.

Three hypothetical cases of obstacles surrounding the release location:

- high congestion: distance between obstacles x=0.2 m, size of obstacles y=0.1 m (unit with multiple tubes and pipelines),
- medium congestion: x=1 m, y=2 m (technological unit surrounded by other units),
- low congestion: x=4 m, y=2 m (a large technological unit surrounded with other technological units, e.g. refueling station).

Results
Release of 10 kg of hydrogen do not result in building damages for the case of the low congestion, but it results in building damages for the case of the medium congestion (at distances of up to 40 m). 10 kg hydrogen release for the case of the high congestion is very severe and results in building damages at distances of up to 70 m.

For the different levels of congestion (low, medium, high) were determined the safety
distances defined by minimum damage for buildings.

A comparison of hydrogen cloud explosion models and the study of the vulnerability of the damage caused by an explosion of H$_2$ [6]


J. Lobato, P. Cañizares, M. A. Rodrigo, Ch. Sáez, J. J. Linares

Faculty of Chemistry, Department of Chemical Engineering, University of Castilla – La Mancha. Campus Universitarios/n. 13004. Ciudad Real, Spain

Objective

The objective of this study is to provide an easy tool for estimation the effects of an unconfined hydrogen cloud explosion as a function of distance. For this purpose it was used three prediction models – TNT equivalency explosion model, TNO multi-energy model, and Baker-Strehlow-Tang model (BST).

Analytical model and conditions

Hydrogen cylinders: 2x60 dm$^3$ with 8.8 m$^3$ of hydrogen,
Hydrogen pressure: 200 bar,
Hole in a pipe: d=1 mm, leakage time 2h before explosion,
Laboratory dimension: 11x8x3 m.

TNT equivalency explosion model: first, the fraction of total energy of explosion used in the shock wave is calculated. Than, it is converted into the equivalent mass of TNT

$$W_{TNT} = \frac{W_{\text{gas}} \eta \Delta H_{c(gas)}}{\Delta H_{c(TNT)}}$$

$W_{TNT}$ (kg) is the equivalent mass of TNT that produce the same effects as the explosion, $\eta$ is the explosion yield, $W_{\text{gas}}$ is the total mass of flammable gas, $\Delta H_{c(gas)}$ (kJ/kg) is the lower heat of combustion of material, $\Delta H_{c(TNT)}$ (kJ/kg) is the heat of combustion of TNT.

TNO multi-energy model: based on premise a vapor cloud explosion occurs only within a partially confined area of flammable vapor. The model is represented as homogenous, stoichiometric mixture hemispherical cloud with a combustion energy 3.1.10$^6$ J/m$^3$ (the average heat of combustion of mixture of hydrogen and air). Results are given as a family of
curves, which represent the range of severities (from deflagrations to detonations).

**Baker-Strehlow-Tang model:** this model also uses a family of curves to relate overpressure to energy scaled distance.

**Results**
The TNT model predicts higher overpressure than the other two models. TNO and BST models predict similar overpressure except areas at very low distances.

---

**Assessment of detonation hazards in high-pressure hydrogen storage from chemical sensitivity analysis [7]**

Hoi Dick Ng\textsuperscript{a}, Yiguang Ju\textsuperscript{a}, John H. S. Lee\textsuperscript{b}

\textsuperscript{a}Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA

\textsuperscript{b}Department of Mechanical Engineering, McGill University, Montréal, Québec, Canada

**Objective**
The objective of this study is to assess a detonation sensitivity of hydrogen-air mixture using kinetic mechanism of hydrogen combustion. This will be helpful for preventing a possible explosion in a high-pressure hydrogen storage facilities when contaminated with air.

**Analytical model and conditions**
The accurate detailed chemical kinetics model is used in this study to quantify the effect of initial pressure on the hydrogen – air detonation sensitivity. The characteristic cell size is considered as a characteristic parameter of detonation sensitivity of mixture:

\[ \chi = \varepsilon_i \frac{\Delta_l}{\Delta_r} = \varepsilon_i \Delta_j \frac{\sigma_{\text{max}}}{u_{\text{ CJ}}} \]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Coefficients of detonation cell size with N=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
<td>Values</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>30.465860763763</td>
</tr>
</tbody>
</table>

---
It is expected cell sizes decrease with increasing initial pressure (probability of detonation increases with pressure). Hydrogen – air mixture does not follow this trend and is not more sensitive than any other hydrocarbon – air mixture at elevated initial pressure.

When the cell size is known it is possible to determine the critical initiation energy for hydrogen – air mixture detonation:

$$ R = \left( \frac{E_{\text{source}}}{\alpha_2 \rho_0} \right)^{\frac{2}{3}} \left( \frac{2 \, \Gamma \, U}{5 \, U} \right)^{\frac{2}{3}} \exp \left( \frac{\beta_2 Q}{3U^2} \right) $$

- $E_{\text{source}}$ Critical direct initiation energy
- $R$ Critical radius (the first explosion bubbles observed)
- $Q$ Heat of reaction
- $U$ Shock velocity
- $\rho_0$ Initial density
- $\alpha_2$ Constant, 0.31246 ($\gamma^{-1}$)$^{1.1409 + 0.11735 \log_{10}(7^{-1})}$
- $\beta_2$ Constant, 4.1263 ($\gamma^{-1}$)$^{1.2530 + 0.14936 \log_{10}(7^{-1})}$
- $\gamma$ Specific heat ratio in mixture

**Results**

The boundary between fast and slow branching regimes for hydrogen – air mixture ($T_0 = 300$ K) was established on initial pressure $p_0 \approx 4$ atm. The chemical kinetics above this pressure is characterized by low branching reaction and small energy release rate. This implies that hydrogen – air mixture at elevated initial pressure is lowly detonation sensitive.

The critical direct initiation energy increases with increasing initial pressure (this again implies mixture is less sensitive at elevated pressure).

In conclusion, the probability of hydrogen – air mixture detonation at elevated initial
pressure is not higher than in other hydrocarbon fuels.

Hydrogen Explosion Study in a Confined Tube: FLACS CFD Simulations and Experiments [8]

21st ICDERS, July 23-27, 2007, Poitiers, France
P. Middhaa-c, O. R. Hansena, M. Groetheb, B. J. Arntzena-c
  aGexCon AS, P.O. Box 6015, Postterminalen, NO-5892 Bergen, Norway
  bSRI International, Poulter Laboratory, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA
  cUniversity of Bergen, Department of Physics and Technology, Allégaten 55, NO-5007 Bergen, Norway

Objective
The objective of this paper is to compare results of numerical simulations and experiments of deflagration a tube geometry (10 m long tube with square section) using the CFD tool FLACS and also investigate the possibilities of deflagration to detonation transition occurrence.

Experiment description and conditions
The experimental facility consisted of 9.9 m long steel tube with square section (dimension 38.1 cm) inside the tube were installed different obstacle (6.35 cm thick, 11.43, 16.51, and 22.86 cm high, spacing between blocks 38.1, 76.2, or 152.4 cm) to induce turbulence. The first block was always located at 38.1 cm from the initiation end. (more about the experiment: M. Groethe, J. Colton, S. Chiba. Hydrogen deflagration safety studies in a confined tube. 14th World Hydrogen Energy Conference, Montreal, Québec, Canada, June 9 – 13, 2002)

Results
The simulations of hydrogen deflagration compare reasonably well with experimental predictions. Very high overpressure (15 – 20 bar) and fast flames makes possible to deflagration to detonation transition. The simulations indicated a deflagration to detonation transition (DDT) at 4 – 5 m from ignition point for hydrogen concentration of 30 % and obstacles 11.43 cm high. DDT was indicated at 3 m from ignition for obstacles 22.86 cm high. Other results are not presented because FLACS lacks a shock ignition model and detonation front cannot propagate.
### 表1. SI基本単位

<table>
<thead>
<tr>
<th>長さ</th>
<th>質量</th>
<th>速度</th>
<th>ワンパワールド</th>
<th>チャージ</th>
<th>磁気</th>
<th>角度</th>
<th>組織</th>
<th>組織</th>
<th>他</th>
<th>SI基本単位による表し方</th>
<th>SI基本単位による表し方</th>
</tr>
</thead>
<tbody>
<tr>
<td>km</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
</tr>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
</tr>
</tbody>
</table>

### 表2. 基本単位を用いて表されるSI単位定義の例

<table>
<thead>
<tr>
<th>組織</th>
<th>長さ</th>
<th>質量</th>
<th>速度</th>
<th>ワンパワールド</th>
<th>チャージ</th>
<th>磁気</th>
<th>角度</th>
<th>組織</th>
<th>組織</th>
<th>他</th>
<th>SI基本単位による表し方</th>
<th>SI基本単位による表し方</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
</tbody>
</table>

### 表3. 固有の名前とその独自の記号で表されるSI単位定義

<table>
<thead>
<tr>
<th>組織</th>
<th>長さ</th>
<th>質量</th>
<th>速度</th>
<th>ワンパワールド</th>
<th>チャージ</th>
<th>磁気</th>
<th>角度</th>
<th>組織</th>
<th>組織</th>
<th>他</th>
<th>SI基本単位による表し方</th>
<th>SI基本単位による表し方</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
</tbody>
</table>

### 表4. 単位の中に固有の名前とその独自の記号を含むSI単位定義の例

<table>
<thead>
<tr>
<th>組織</th>
<th>長さ</th>
<th>質量</th>
<th>速度</th>
<th>ワンパワールド</th>
<th>チャージ</th>
<th>磁気</th>
<th>角度</th>
<th>組織</th>
<th>組織</th>
<th>他</th>
<th>SI基本単位による表し方</th>
<th>SI基本単位による表し方</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m</td>
<td>s</td>
<td>T</td>
<td>rad</td>
<td>m</td>
<td>mol</td>
<td>cd</td>
<td>m</td>
<td>s</td>
<td></td>
</tr>
</tbody>
</table>

### 表5. SI接頭語

<table>
<thead>
<tr>
<th>倍数</th>
<th>接頭語</th>
<th>数字</th>
<th>接頭語</th>
<th>記号</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^4</td>
<td>ヨーフォマラ</td>
<td>1</td>
<td>ヨーフォマラ</td>
<td>1</td>
</tr>
<tr>
<td>10^3</td>
<td>ヨーフォマラ</td>
<td>2</td>
<td>ヨーフォマラ</td>
<td>1</td>
</tr>
<tr>
<td>10^2</td>
<td>ヨーフォマラ</td>
<td>3</td>
<td>ヨーフォマラ</td>
<td>1</td>
</tr>
<tr>
<td>10^1</td>
<td>ヨーフォマラ</td>
<td>4</td>
<td>ヨーフォマラ</td>
<td>1</td>
</tr>
</tbody>
</table>

### 表6. 国際単位系と併用されるが国際単位系に属さない単位

<table>
<thead>
<tr>
<th>名称</th>
<th>SI単位で表わされる数値</th>
</tr>
</thead>
<tbody>
<tr>
<td>ノット</td>
<td>1ノット=1海里每秒（1852/3600）</td>
</tr>
<tr>
<td>ケルビン</td>
<td>1ケルビン=1℃</td>
</tr>
<tr>
<td>ベル</td>
<td>1ベル=0.1分</td>
</tr>
<tr>
<td>オンス</td>
<td>1オンス=0.02834656kg</td>
</tr>
</tbody>
</table>

### 表7. 国際単位系と併用されない国際単位系と使用される他の単位

<table>
<thead>
<tr>
<th>名称</th>
<th>SI単位で表わされる数値</th>
</tr>
</thead>
<tbody>
<tr>
<td>エル</td>
<td>1エル=10^-8</td>
</tr>
<tr>
<td>ダイン</td>
<td>1ダイン=10^-5</td>
</tr>
<tr>
<td>ボルト</td>
<td>1ボルト=6.283185307×10^7</td>
</tr>
<tr>
<td>セルシウス温度</td>
<td>1℃=1K</td>
</tr>
<tr>
<td>ルーメン</td>
<td>1ルーメン=1lm</td>
</tr>
<tr>
<td>クール</td>
<td>1クール=1lx</td>
</tr>
<tr>
<td>ピクル</td>
<td>1ピクル=1μlx</td>
</tr>
</tbody>
</table>

### 表8. 国際単位系に属さないが国際単位系と使用される他の単位

<table>
<thead>
<tr>
<th>名称</th>
<th>SI単位で表わされる数値</th>
</tr>
</thead>
<tbody>
<tr>
<td>キュリ</td>
<td>1キュリ=10^-7</td>
</tr>
<tr>
<td>レントゲン</td>
<td>1レントゲン=1erg</td>
</tr>
<tr>
<td>レル</td>
<td>1レル=10^-7</td>
</tr>
<tr>
<td>ルクス</td>
<td>1ルクス=1lx</td>
</tr>
<tr>
<td>ポルト</td>
<td>1ポルト=10^9</td>
</tr>
</tbody>
</table>

### 表9. 国際単位系に属さないその他の単位

<table>
<thead>
<tr>
<th>名称</th>
<th>SI単位で表わされる数値</th>
</tr>
</thead>
<tbody>
<tr>
<td>キュリ</td>
<td>1キュリ=10^-7</td>
</tr>
<tr>
<td>レントゲン</td>
<td>1レントゲン=1erg</td>
</tr>
<tr>
<td>レル</td>
<td>1レル=10^-7</td>
</tr>
<tr>
<td>ルクス</td>
<td>1ルクス=1lx</td>
</tr>
<tr>
<td>ポルト</td>
<td>1ポルト=10^9</td>
</tr>
</tbody>
</table>