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Pelletized Cold Neutron Moderators for the IBR-2M reactor

Presented by
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Contents

1. Solid mesitylene cold moderator, comparative performance of mesitylene to methane.

2. Preparation and transport of solid mesitylene balls.

3. Current status of the mesitylene cold moderator project.
Solid mesitylene as a cold moderator

Benzene

Tm = 278 K

Toluene

Tm = 180 K

Mesitylene

Tm = 227 K

Aromatic hydrocarbon 1,3,5 – trimethylbenzene.

Tm – melting point
Solid mesitylene as a cold moderator

Mesitylene

$T_m = 227 \text{ K}$

$m$-xylene

$T_m = 225 \text{ K}$

Mixture with $m$-xylene or pseudocumene is of glassy structure, and has good neutron thermalization property.
Solid mesitylene cold moderator

Density of vibrational states (by I. Natkaniec)

<table>
<thead>
<tr>
<th>G(ν)</th>
<th>Energy transfer - ν [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M:m-X = 3:1 volume solution</td>
<td></td>
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<tr>
<td>Mesitylene (M) - crystal phase I</td>
<td></td>
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<tr>
<td>m-xylene (m-X) - crystal phase</td>
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</table>
Solid mesitylene cold moderator

Density of states for methane and TMB mixture

\[ G(\nu) \text{ [a.u.]} \]

Neutron energy transfer - \( \nu \) [meV]

T = 20K

- methane - CH\(_4\)
- 1,3,5:1,2,4-TMB = 3:2 volume solution

H\(_2\)O:CH\(_3\)OH = 1:1 volume solution

NORM: number of H atoms = 10

monitor counts = 10
Calculated neutron fluxes from methane (2) and mesitylene (1) cold moderators

1. Mesitylene 3 cm at T = 20K,
2. Methane 2 cm at T = 60K

Note: To avoid problems with hydrogen and burps, methane should be used at T > 60 K and at fast neutron flux < 10**12 n/cm^2/s
Radiolytic hydrogen production:

*in solid methane:*

- $6 \times 10^{-7}$ mol/J for absorbed dose $\leq 1$ kJ/g;
- $3 \times 10^{-7}$ mol/J for absorbed dose $>> 10$ kJ/g.

*in mesitylene:*

- $3.9 \times 10^{-8}$ mol/J = 11.7% of solid methane;
- in mesitylene + toluene, 50 by 50%:
- $1.8 \times 10^{-8}$ mol/J $^*$ = 5.5% of methane.
Pressure of hydrogen on walls of a moderator chamber.

- During annealing (or burping), gas of radiolytic hydrogen expands and builds up pressure inside of matrix and on the walls of the chamber.

- This pressure in solid methane was measured as high as ~1 bar/hour as compared to that value for mesitylene ~0.1 bar/hour at the same absorbed dose rate.
Spontaneous reaction of recombination of radicals in water ice samples

Segment 7.5 мм, Tirr. = 11 h

Segment 7.5 мм, Tirr. = 10.5 h
No spontaneous reaction of recombination of radicals in mesitylene samples

Сегмент H=7.5 мм, Время облуч. = 8 h, T = 20 K

При облучении в течении 45 часов при T=20K ни спонтанной ни индуцированной реакции рекомбинации не наблюдалось
### Properties of mesitylene:

- **Density** at 20°C – 0.86 g/cm³, at 20 K ~1 g/cm³
- **Heat capacity** at 20 K - 0.2 J/g/K, at 80 K - 0.6 J/g/K.
- **Melting temperature and heat** – 228 K and 100 J/g
- **Vaporization temperature and heat** at p=1 бар – 437 K and 320 J/g
- **Thermal conductivity** at 20K - 40 K – 0.2 W/m/K
Concept of Pelletized Cold Moderator

1 – moderator chamber
2 – tube for charging of balls
3 – ball dosing device
4 – ball production device
5 – heat exchanger
6 – helium blower
7 – helium pipes of the primary loop
8 – used mesitylene bin
9 – the secondary loop
Solid balls of the frozen mixture of mesitylene and m-xylene

Method of solid ball production is based on freezing of droplets in liquid nitrogen.

Diameter of the balls is 5 mm
Transportation of mesitylene balls

General equation for moving of a ball with gas flow in the straight pipe is:

\[
\frac{dV_{ball}}{dt} = -g(sin(\alpha) + k(cos(\alpha)) \cdot (1 - \frac{\rho_{gas}}{\rho_{ball}}) - C_{am} \cdot \frac{\rho_{gas}}{\rho_{ball}} \cdot \frac{d(V_{ball} - V_{gas})}{dt}
\]

\[
-0.75 \cdot k \cdot \left( \frac{\rho_{gas}}{\rho_{ball} d_{ball}} \right) \cdot V_{gas}^2 \cdot C_N \left( \frac{V_{ball} - V_{gas}}{V_{gas}}, Re_{pipe}, \frac{d_{ball}}{d_{pipe}}, \omega, \ldots \right) \cdot sign(C_N) +
\]

\[
+ 0.75 \cdot \left( \frac{\rho_{gas}}{\rho_{ball} d_{ball}} \right) \cdot V_{gas}^2 \cdot C_D \left( \frac{V_{ball} - V_{gas}}{V_{gas}}, sign\left( \frac{V_{ball} - V_{gas}}{V_{gas}} \right), Re_{pipe}, \frac{d_{ball}}{d_{pipe}}, \omega, \ldots \right)
\]
Transportation of mesitylene balls

Averaged speed of gas is 10 m/s; the ball is stopped.

Averaged speed of gas is 8 m/s; the speed of the ball – 3 m/s.
By computer simulation of gas flow with a separate ball inside cylindrical tube, characteristics of hydrodynamics and forces onto a ball was calculated.

\[ F_{\text{gasX}} = \rho_{\text{gas}} \frac{v_{\text{gas}}^2}{2} \cdot S \cdot C \left( \frac{v}{v_{\text{gas}}}, \frac{d}{D}, Re \right) = \rho_{\text{gas}} \frac{v_{\text{gas}}^2}{2} \cdot S \cdot (1 - b \cdot \frac{v}{v_{\text{gas}}} + f \cdot \left( \frac{v}{v_{\text{gas}}} \right)^2) \cdot C(0) \]
Transportation of mesitylene balls

Simplified, analytically soluble equation for transport of a ball in the straight pipe is:

\[ \frac{dV}{dt} = -g(\sin(\alpha) + k \cos(\alpha)) + 0.75 \cdot \frac{\rho_{\text{gas}}}{\rho_{\text{ball}} d_{\text{ball}}} \cdot v_{\text{gas}}^2 (1 - A v / v_{\text{gas}}) C(0) \]

where factor \( A < 1 \) is weakly depend on \( Re \) and \( d_{\text{ball}} / d_{\text{pipe}} \), and \( C(0) \) is a drag force factor for the stopped ball.

It is clear that it’s possible to simulate mesitylene beads transport by 80 K helium gas with transportation of glass beads of the same size with flow of room temperature nitrogen due to equality of the complex in the brackets.
Transportation of ideal solid balls

Computer hydrodynamic model:

Speed of a ball (d=5 mm) moving in a straight pipe (d=17 mm) with gas flow 11 m/s versus time.

Black curves – sliding of the ball with friction factors k=0.05 and k=0.1; the blue curve – rolling of the ball.

Magenta – analytic calculation for k=0.05
Experiment versus theory:

Calculated values of the drag coefficient agree well with the experimental values in the range 0-50% of the speed of gas flow, showing the rolling character of a ball motion.

BUT.....
“Acceleration versus speed” of a ball at 11 m/s gas velocity.

Red and black symbols – experiment, green – theory for rolling of ideal ball along a pipe with ideally smooth walls.
Pieso-electric transducers fasten to the tube showed that fast moving balls start to bounce and lose their velocity.

Kinetic energy of the ball dissipates due to friction forces:

\[ F_L = (2 \frac{mV_0}{t}) \cdot k \cdot (V_L \cdot t) = m \cdot V^2 \sin 2\alpha \cdot k \]

\[ \frac{\Delta E}{E} = - \frac{m \cdot V^2 \sin 2\alpha \cdot k}{m \cdot V^2 / 2} = -2 \sin 2\alpha \cdot k \]

At \( \alpha = 1/6 \) and \( k = 0.33 \), \( \frac{\Delta E}{E} = -0.217 \)
Speed of ball, m/s, at $V_{gas}=8$ m/s; $x=100 - 2.9$ m from the start.
Scheme of the IBR-2 (left) and IBR-2M reactors

*green marks moderator area*

IBR-2M is more compact, 1.7 gain in flux
Lay-out of the moderator complex and vertical section of the moderators at the central direction
1. Chamber of the cold moderator
2. Light water pre-moderator;
3. Flat water reflector
4. Outer border of the reactor;
No 4, 5, 6, 1, 9 – numbers of neutron beams

Combi-moderator at the central direction of the IBR-2M reactor, plan view
Neutron moderator for beams #2, 3

Water premoderator

Mesitylene pelletized moderator chamber

Drained chamber
Differential flux density at the surface of the three moderators

\[ \text{n/eV/sr/cm}^2/\text{sec} \]

Energy, eV

- beam 8
- beam 2
- beam 5
Scalar neutron flux distribution at the surface of the cold moderator

a) – thermal neutrons, b) – cold neutrons
# Intense sources for research on extracted neutron beams

<table>
<thead>
<tr>
<th></th>
<th>Grenoble</th>
<th>ISIS (second target)</th>
<th>ИБР-2М</th>
<th>SNS 2007-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal power, MW</strong></td>
<td>60</td>
<td>0.04</td>
<td>2</td>
<td>1.4 ÷ 2</td>
</tr>
<tr>
<td><strong>Cold neutron flux</strong></td>
<td>50</td>
<td>~ 0.6</td>
<td>1.0</td>
<td>~ 3 ÷ 4</td>
</tr>
<tr>
<td>(Φ), 2π equivalent, (\text{н/с/см}^2), (10^{12})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cold neutrons per pulse</strong></td>
<td>~ 1</td>
<td>~ 3</td>
<td>28</td>
<td>~ 12 ÷ 15</td>
</tr>
<tr>
<td>(long wavelengths)</td>
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- Cold neutron flux: \(\Phi\cdot S / f \cdot 10^{12}\) (in 200 μs, 100 cm\(^2\))
- Preference due to big moderator area and low pulse frequency.
At engineering plant “Heliummash”, manufacturing of the new refrigerator facility KGU-700/15 is finished.

- Fabrication of systems for manufacturing, charging and discharging of mesitylene beads are in progress at the Lab. Neutron Physics of JINR.

- In RDIPE a preliminary design of the moderators complex for the IBR-2M is accomplished.

- Cryogenic pipelines from the cryogenic facility KGU-700/15 up to the moderators are in fabrication.
With Cold Moderator
- toward North Pole!
Conveying of balls

Velocity of balls along transport pipe to the moderator chamber at 5 m/s gas velocity (project)
Filling the chamber without deflector (left) and with the deflector of an optimized size and inclination (right)
Speed of ball at 5 m/s gas flow (no jumps of a ball)

$Y = 2.48547 + 4.88495 \times 10^{-4} \times X$

Y Axis Title

position of a ball, mm

- D
- B
- Polynomial Fit of Data1_D
Present status of the Complex of Moderators for the IBR-2M

- Theory of transportation of balls by gas flow in a pipe along a path of complicated shape is derived; experimental confirmation is in progress.

- *Method of solid ball mass production is developed; ball generator is designed and fabricated.*

- Design of a ball dosing machine to enter them into the transport pipe is worked out; techniques was previously confirmed with a mock-up.
Транспорт шариков – обработка опытов при скорости газа 5 м/с

\[ a_{\text{exp}} = 0.83 - 0.238 \, v \]

\[ a_{\text{thor}} = 0.78 - 0.21 \, v \]
$Y = 1.56891 - 0.17689 \times X$

- acceleration at 8 m/s
- Fitting of acceleration law
- Green dots: Rolling ball, theory at 8 m/s
Differential flux density at the direction of the beam # 7 at 4.5 m off the source.