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Development of Simple Evaluation Method for Duct Streaming

Koichi Maki† and Kei-ichiro Shibata

* *Power & Industrial Systems R & D Laboratory, Power & Industrial Systems, Hitachi, Ltd.,*

A simple formula for radiation streaming through bent ducts is derived by optics analogy with considering only components passing through the duct not required for enormous preparatory calculations. Dose rates estimated by the derived formula are compared with experimental values in two types of two-stage bent ducts for gamma-ray source and four types of one-stage bent ducts for 14MeV neutron source. Regarding the two-stage, 45-degree bent duct with a diameter of 15cm, estimated dose rates at the positions of the bend points and the exit agree with the experimental values within 30% and a factor of 2, respectively. Regarding the two-stage, 90-degree bent square duct with a 1.8m side, estimated dose rates at the positions of the bend points and the exit agree with the experimental values within 30%. For 90-degree one-stage bent square ducts with 10cm, 20cm and 40cm sides in iron and polyethylene shields with 14MeV neutron source, dose rates by the formula agree with experimental values within factor 3 at the exit. From these results, it is concluded that the derived formula is applicable to the midway in shielding design.

KEYWORDS: radiation streaming, duct streaming, simplified formula, bent duct

I. Introduction

For fusion and accelerator facilities producing neutron and gamma-ray, there are many ducts and slits in the facilities. In fusion facilities, there are various ducts for plasma heating equipment such as neutral beam injectors, diagnostic tools and their cables, and radio frequency guide tubes, etc. Accelerators have various ducts for electric power cables and as passages in the accelerator buildings. Therefore, radiation shielding is important with regard to radiation streaming through these ducts.

Though radiation shielding is analyzed by three-dimensional codes for the final radiation shielding design, three-dimensional calculations are not always the best way to examine an intermediate design because of enormous time spent for three-dimensional codes like Monte Carlo codes and discrete ordinate transport codes. Then a simplified evaluation formula is earnestly desired to evaluate radiation streaming properties effectively, midway in the design process.

Various simplified evaluation formulae for radiation streaming have been derived [1-9]. But the desired degree of simplification cannot always be achieved in most of them, since enormous preparatory calculations are necessary to estimate the radiation shielding properties for using the formulae.

The present paper proposes a simplified radiation duct streaming formula which does not need many preparatory calculations. We applied analogy of optics to radiation streaming phenomena through various shaped bent ducts in order to simplify the formula. Configurations of the duct cross section are restricted to those which are nearly circular or regular squares and the streaming components mainly contributing to the dose rate behind radiation shielding are also restricted. The derived simplified formula is applied to six typical configurations of ducts with one or two bends and the obtained dose rates are compared with experimental values.

* *7-2-1Omika-cho, Hitachi-shi, Ibaraki-ken, 319-1221*
† Corresponding author, Tel.+81-294-53-3111 ext.5266, Fax. +81-294-53-9583, E-mail: kmaki@erl.hitachi.co.jp

In section 2, the simplified duct streaming formula is derived. In section 3, shielding properties calculated by the derived formula are compared with experimental values for the two configurations of ducts with two bends with gamma-ray source and for the four configurations of ducts with one bend with 14MeVneutron source.

II. Derivation of Simplified Duct Streaming Formula

1. Restriction for Simplification

As described in the Introduction, in order to derive a duct streaming formula which is as simple as possible, the optics analogy is applied and the following restrictions are set.

The cross sections are restricted to nearly circle or regular squares and the length from one bend to the other bend is assumed to be much longer than the principal length of the cross section (diameter of the circle or side length of the square).

The duct streaming components make their main contribution to the dose rate behind the shielding and only the streaming components are considered in the formula.

Simplified duct streaming formula for cosine distributions at the bend position are approximated by assuming large forward scattering such as the Compton scattering angular distribution for about 1MeV and high energy neutron above several MeV. Factors f_n by anisotropic scattering at each bend point are given as a function of the bend angle θ_n. In the present paper, $F_n(q_n)$ is approximated as a cosine distribution of $cos(\theta_n/2)$,

$$f_n = F_n(\theta_n) = cos(\theta_n/2), \tag{1}$$

where f_n means an anisotropic factor at the bend point P_{n-1} between the (n-1)-th and the n-th legs and θ_n means the bend angle made from the direction of the (n-1)-th leg to the direction of the n-th leg at the point P_{n-1}. as shown in **Fig. 1**.

2. Simplified Model

In **Fig. 1** the radiation source intensity and its position is symbolized by S, and the point at the entrance of the first leg,

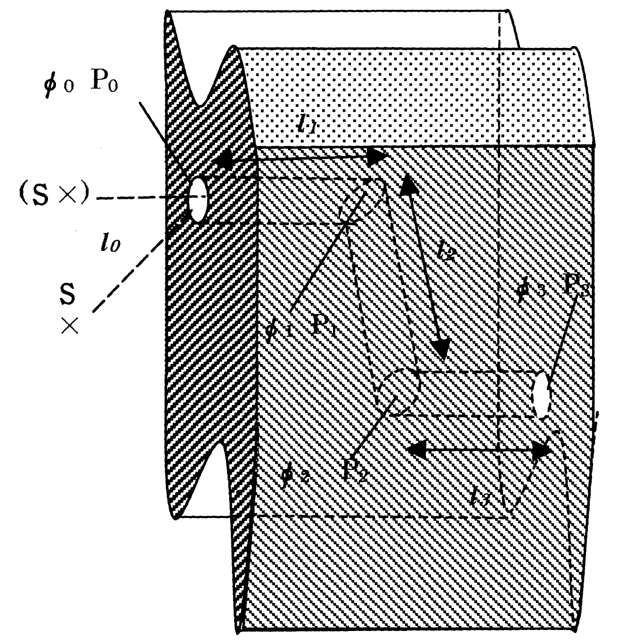

Fig. 1 Configuration of bent duct model

the bend point of the first and second legs, • • •, the bend point of the (n-1)-th and n-th legs, and the exit point of n-th leg are identified as P_0, P_1, • • •, P_{n-1} and P_n, respectively. The parenthesized source position where the source can be seen from the bottom of the first leg is treated as a distinct case from that where the source cannot be seen from the bottom.

Radiation fluxes at the points P_0, P_1, P_2, P_3, • • •, P_{n-1} and P_n, are symbolized as ϕ_0, ϕ_1, ϕ_2, ϕ_3,• • •, ϕ_{n-2}, ϕ_{n-1} and ϕ_n, respectively. The equivalent radii and lengths of the first, the second, • • •, the (n-1)-th and the n-th legs are described as r_1,r_2,r_3,• • •,r_{n-1} and r_n, and l_1, l_2, l_3,• • •, l_{n-1} and l_n, respectively.

(1) The case where the source cannot be seen from the bottom of the first leg

We assume the out of parenthesized point source, then radiation flux ϕ_0 at point P_0 is given as,

$$\phi_0 = \frac{S}{4\pi {l_0}^2}, \tag{2}$$

where S is the radiation source intensity, and l_0 is a distance from P_0 to the source. An imaginary radiation source intensity S_0 at point P_0 is given by f_0 in accordance with the optics analogy as,

$$S_0 = \pi {r_1}^2 \phi_0 = \frac{1}{4}\left(\frac{r_1}{l_0}\right)^2 S. \tag{3}$$

Using Eq. (2), we describe ϕ_1 at the point P_1 as,

$$\phi_1 = \frac{S_0}{4\pi l_1^2} f_1 = \frac{1}{4}\left(\frac{r_1}{l_1}\right)^2 \phi_0 f_1 = \frac{S}{4\pi {l_0}^2}\left(\frac{1}{4}\right)\left(\frac{r_1}{l_1}\right)^2 f_1. \tag{4}$$

where f_1 expresses the distribution in the direction of the angle θ_0 made by the line between the source and point P_0 to the first leg. Using Eq.(4) as expressed above, we give imaginary source intensity S_1 at point P_1 as,

$$S_1 = \pi {r_2}^2 \phi_1 = \left(\frac{1}{4}\right)^2\left(\frac{r_2}{l_0}\right)^2\left(\frac{r_1}{l_1}\right)^2 S f_1, \tag{5}$$

and radiation flux ϕ_2 at point P_2 as,

$$\phi_2 = \frac{S_1}{4\pi {l_2}^2} f_2 = \frac{1}{4}\left(\frac{r_2}{l_2}\right)^2 \phi_1 f_2$$

$$= \frac{S}{4\pi {l_0}^2}\left(\frac{1}{4}\right)^2\left(\frac{r_1}{l_1}\right)^2\left(\frac{r_2}{l_2}\right)^2 f_1 f_2, \tag{6}$$

By analogy to the above, radiation fluxϕ_n at the exit point of the n-th leg can be obtained as,

$$\phi_n = \frac{S_{n-1}}{4\pi l_n^2} f_n = \frac{1}{4}\left(\frac{r_{n-1}}{l_{n-1}}\right)^2 \phi_{n-1} f_n$$

$$= \frac{S}{4\pi l_0^2}\left(\frac{1}{4}\right)^n \prod_{i=1}^{n}\left(\frac{r_i}{l_i}\right)^2 f_i, \tag{7}$$

(2) The case where the source can be seen from the bottom of the first leg

When the source can be seen from the bottom of the first leg (Fig. 1), a direct effect of the source on the flux ϕ_1 at point P_1 must be taken into consideration together with the indirect effect described in subsection (1).

Radiation flux ϕ_0 at point P_0 by the indirect effect of the source S is given by the following equation in the same manner as detailed in subsection (1),

$$\phi_0 = \frac{S}{4\pi {l_0}^2}. \tag{8}$$

Using this equation, we express the imaginary source intensity S_0 at point P_0 as the following equation,

$$S_0 = \pi {r_1}^2 \phi_0 = \frac{1}{4}\left(\frac{r_1}{l_0}\right)^2 S. \tag{9}$$

The direct effect of the source S on the flux ϕ_1 at point P_1 is made by radiation at the bottom of the first leg, spreading from the source S in the total space as,

$$S / 4\pi (l_0 + l_1)^2. \tag{10}$$

Considering both effects of Eqs. (9) and (10), we give radiation flux ϕ_1 at the point P_1 as,

$$\phi_1 = \left(\frac{S_0}{4\pi l_1^2} + \frac{S}{4\pi (l_0 + l_1)^2}\right) f_1$$

$$= \frac{S}{4\pi l_0^2 \cdot 4}\left(\frac{r_1}{l_1}\right)^2\left[1 + \left\{\frac{2 l_1 l_0}{r_1 (l_0 + l_1)}\right\}^2\right] f_1$$

$$= \frac{1}{4}\left(\frac{r_1}{l_1}\right)^2\left[1 + \left\{\frac{2 l_1 l_0}{r_1 (l_0 + l_1)}\right\}^2\right] \phi_0 f_1. \tag{11}$$

The imaginary source intensity S_1 at point P_1 is given as,

$$S_1 = \pi {r_2}^2 \phi_1$$

$$= \frac{S}{4}\left(\frac{r_2}{l_0}\right)^2\left(\frac{1}{4}\right)\left(\frac{r_1}{l_1}\right)^2\left[1 + \left\{\frac{2 l_1 l_0}{r_1 (l_0 + l_1)}\right\}^2\right] f_1. \tag{12}$$

Using this equation, we write radiation flux ϕ_1 at point P_2 as,

$$\phi_2 = \frac{S_1}{4\pi l_2^{\,2}} f_2 = \frac{1}{4}\left(\frac{r_2}{l_2}\right)^2 \phi_1 f_2$$

$$= \frac{S}{4\pi l_0^{\,2}}\left(\frac{1}{4}\right)^2\left(\frac{r_2}{l_2}\right)^2\left(\frac{r_1}{l_1}\right)^2\left[1+\left\{\frac{2l_1 l_0}{r_1(l_0+l_1)}\right\}^2\right] f_1 f_2 \cdot \quad (13)$$

By analogy to the above, radiation flux ϕ_n at the exit point of the n-th leg can be obtained as,

$$\phi_n = \frac{S_{n-1}}{4\pi l_n^{\,2}} f_n \cdot$$

$$= \frac{S}{4\pi l_0^{\,2}}\left(\frac{1}{4}\right)^n \prod_{i=1}^{n}\left(\frac{r_i}{l_i}\right)^2\left[1+\left\{\frac{2l_1 l_0}{r_1(l_0+l_1)}\right\}^2\right] f_i . \quad (14)$$

III. Comparison with Experimental Values

In this section we compare values estimated by the proposed formula with experimental streaming values. Duct streaming experiments for two typical bent ducts have been performed for the gamma-ray source [10,11]. One was a streaming experiment through a two-bend medium sized duct with 45-degree bend angles[10]. The other was a streaming experiment through a two- bend large aperture duct with 90-degree bend angles[11]. As for duct streaming by neutron, one-time bent duct streaming experiments have been performed for 14MeV neutron source by OKAVIAN facility[13,14]. These duct configurations are illustrated in **Table 1**.

Radiation fluxes ϕ_n are estimated by the simplified streaming formula derived in section 2. Multiplying the fluxes ϕ_n by conversion factors for flux into dose rates, we can obtain dose rates. Assuming the energy spectrum of the flux to be approximately the same at every position inside the ducts, the relative value of the flux at every position to that at the entrance of the duct can be considered to be represent a relative dose rate. The relative dose can be then compared with the relative dose rate at every position to that at the entrance for calculations and experiments.

From these geometrical configurations, the relative dose rates are estimated by the present formula. The dose rates are compared with observed values in **Tables 2 - 7** and **Figs. 2 – 5**.

From the comparisons of the values by the present simplified formula with the experimented values for the six duct configurations, the formula validity can be evaluated.

1) For 45-degree bent duct with medium radius of 15cm in gamma-ray source, both dose rates agree with each other within 30% at every bend point and less than factor 2 at the exit.
2) For 90-degree bent square duct with 1.8m side in gamma-ray source, both dose rates agree with each other within 30% at every bend and at the exit for the anisotropic approximation. The approximation of $f_n = cos(\theta_n/2)$ is a good approximation. Energy and material dependences of these anisotropic factors will be investigated more in the future.
3) For 90-degree one-time bent square ducts with 10cm and 20cm sides in iron shields with 14MeV neutron source, dose rates by the anisotropic approximation at the exit has a

Table 1 Various duct configurations used in comparing relative dose rates by this formula with experimental ones

duct name / configuration	Two-stage 45-degree bent duct with 15cm radius in concrete shield[10]	Two-stage 90-degree bent square duct with1.8m-side in concrete shield[11]	One-stage 90-degree bent square duct with 10cm-side in iron shield([13]	One-stage 90-degree bent square duct with 20cm-side in iron shield[13]	One-stage 90-degree bent square duct with 10cm-side in polyethylene shield[14]	One-stage 90-degree bent square duct with 40cm-side in polyethylene shield[14]
radiation source	1.33 and 1.1 7 MeV gamma-ray from ^{60}Co	1.33 and 1.1 7 MeV gamma-ray from ^{60}Co	14MeV from DT reaction	14MeV from DT reaction	14MeV from DT reaction	14MeV from DT reaction
and its position	18.5cm far from the inlet of the first leg on its axis	0.9m inside the inlet of the first leg	9.4cm far from the inlet of the first leg on its axis	9.4cm far from the inlet of the first leg on its axis	9.4cm far from the inlet of the first leg on its axis	9.4cm far from the inlet of the first leg on its axis
diameter of the duct	15cm	1.8m(equivalent radius of 1.02m)	10cm(equivalent radius of 5.6cm)	20cm(equivalent radius of 11.3cm)	10cm(equivalent radius of 5.6cm)	40cm(equivalent radius of 22.6cm)
the first leg length	53.6cm	3.9m	70cm	70cm	100cm	100cm
angle	45 degrees	90 degrees	90 degrees	90 degrees	90 degrees	90 degrees
the second leg length	97cm	4.2m	70cm	70cm	150cm	150cm
angle	45 degrees	90 degrees				
the third leg length	53.6cm	2.0m				

Table 2 Comparison of relative dose rates by the simplified streaming formula with those by experiments in 45 degree two times bending duct with radius of 15cm in concrete for the gamma-ray sources from ^{60}Co.

position	estimated values by the simplified streaming formula	observed values[11]	calculated values(*)
10cm from entrance	1.0	1.0	1.0
the first joint	1.0×10^{-1}	1.3×10^{-1}	1.3×10^{-1}
the second join	1.4×10^{-4}	1.3×10^{-4}	1.3×10^{-4}
the exit	6.2×10^{-7}	1.4×10^{-6}	6.0×10^{-7}

(*) estimated by point kernel interaction code of RANKERN [12].
(**) anisotropical factor $f_n=F_n(\theta_n)=cos(45/2)$=0.92 is used.

Table 3 Comparison of relative dose rates by the simplified streaming formula with those by experiments in 90 degree two times bending square duct with 1.8m side of the equivalentradius of 1.02m for the gamma-ray sources from ^{60}Co and ^{137}Cs.

position	estimated values by the simplified streaming formula	observed values[11]
source position	1.0	1.0
the first joint	8.6×10^{-2}	8.0×10^{-2}
the second join	8.9×10^{-4}	7.0×10^{-4}
the exit	4.2×10^{-5}	3.5×10^{-5}

(*) anisotropical factor $f_n=F_n(\theta_n)=cos(90/2)$=0.70 is used.

Table 4 Comparison of relative dose rates by the simplified streaming formula with those by experiments in 90 degree one time bending square duct with 10cm side of the equivalent radius 5.6cm in iron shield for 14MeV neutron source.

position	estimated values by the simplified streaming formula	observed values[13]
0 cm	1.0	1.0
30cm	6.6×10^{-2}	1.1×10^{-1}
60cm	2.1×10^{-2}	1.5×10^{-2}
90cm	1.9×10^{-4}	1.1×10^{-3}
110cm	5.7×10^{-5}	1.6×10^{-4}
130cm	2.8×10^{-5}	5.0×10^{-5}

(*) anisotropical factor $f_n=F_n(\theta_n)=cos(90/2)$=0.70 is used.

discrepancy of greater than 40% with the experimental value. The dose rates by the anisotropic approximation in the latter are under estimated by the factor 3 for the experimental value.

4) For 90-degree one-time bent ducts with 10cm and 40cm sides in polyethylene shields with 14MeV neutron source, dose rates at the joint by simple formula agree with the observed values within 20%. The dose rates by the isotropic and anisotropic approximations at the exit in the former are under estimated by the factors 2 and 3, respectively, for the experimental values. In the latter, the dose rate by anisotropic approximation at the exit agrees with the experimental value within 10%.
5) The present streaming formula was derived by the optics analogy together with restricting streaming components contribution to the dose rate. The formula can reproduce the experimental values within factor 3 in exits and can be applied as a tool in the midway of shielding design for near 1MeV gamma-ray and fusion neutron with14 MeV energy.

Table 5 Comparison of relative dose rates by the simplified streaming formula with those by experiments in 90 degree one time bending square duct with 20cm side of the equivalent radius 11.3cm in iron shield for 14MeV neutron source.

position	estimated values by the simplified streaming formula	observed values[13]
0 cm	1.0	1.0
30cm	9.2×10^{-2}	9.9×10^{-2}
60cm	2.0×10^{-2}	2.1×10^{-2}
90cm	1.1×10^{-3}	5.4×10^{-3}
110cm	2.8×10^{-4}	1.1×10^{-3}
130cm	1.3×10^{-4}	3.5×10^{-4}
140cm	9.1×10^{-5}	3.0×10^{-4}

(*) anisotropical factor $f_n=F_n(\theta_n)=cos(90/2)$=0.70 is used.

Table 6 Comparison of relative dose rates by the simplified streaming formula with those by experiments in 90 degree one time bending square duct with 10cm side of the equivalent radius 5.6cm in polyethylene shield for 14MeV neutron source.

position	estimated values by the simplified streaming formula	observed values(14)
0 cm	1.0	1.0
30cm	6.6×10^{-2}	8.8×10^{-2}
60cm	2.1×10^{-2}	2.5×10^{-2}
100cm	8.3×10^{-3}	1.0×10^{-2}
130cm	7.7×10^{-5}	1.9×10^{-4}
168cm	1.2×10^{-5}	3.8×10^{-5}

(*) anisotropical factor $f_n=F_n(\theta_n)=cos(90/2)$=0.70 is used.

Table 7 Comparison of relative dose rates by the simplified streaming formulae with those by experiments in 90 degree one time bending square duct with 40cm side of the equivalent radius 22.6cm in polyethylene shield for 14MeV neutron source.

position	estimated values by the simplified streaming formula	observed values[14]
0 cm	1.0	1.0
30cm	1.9×10^{-1}	1.3×10^{-1}
60cm	5.2×10^{-2}	5.0×10^{-2}
100cm	2.0×10^{-2}	2.5×10^{-2}
121cm	2.0×10^{-2}	2.5×10^{-2}
142cm	3.3×10^{-3}	3.3×10^{-5}
189cm	2.9×10^{-4}	4.2×10^{-4}
240cm	9.1×10^{-5}	8.3×10^{-5}

(*) anisotropical factor $f_n=F_n(\theta_n)=cos(90/2)$=0.70 is used.

IV. Conclusion

A simplified radiation duct streaming formula which does not required many preparatory calculations was proposed by optics analogy, restricting where the streaming components have a main contribution to the dose rate. The derived formula was used to estimate dose rates in the two typical two-bent ducts for gamma-ray source and four typical one-bent ducts for 14 MeV neutron source. One of the two-bent ducts was a circular cross section duct with 45-degree bend angles and radius of

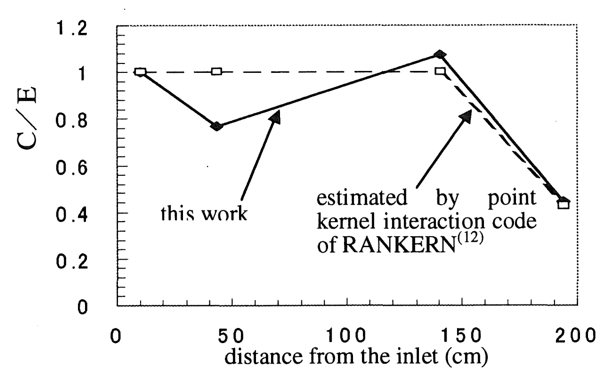

Fig. 2 Comparison of relative dose rates by this formula with experimental values in two stage 45-degree circular bent duct with radius of 15cm in concrete shield.

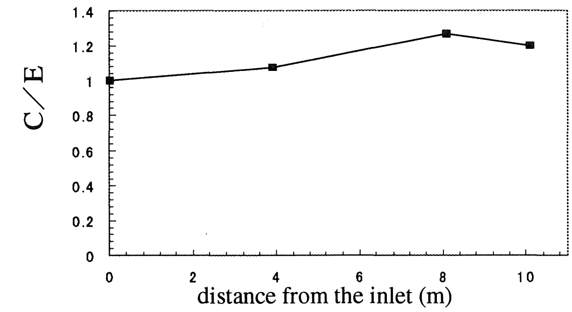

Fig. 3 Comparison of relative dose rates by this formula with experimental values in two stage 90-degree square bent duct with equivalent radius of 102 m in concrete shield

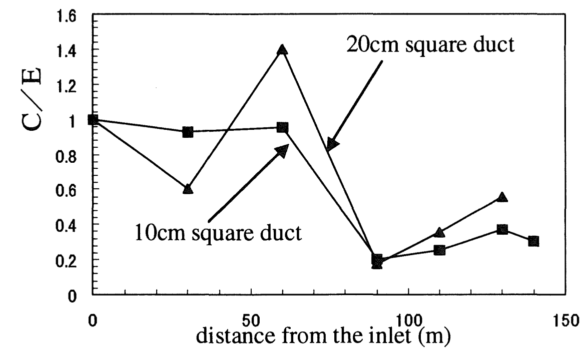

Fig. 4 Comparison of relative dose rates by this formula with experimental values in one stage 90-degree square bent duct with 10cm- and 20cm-side in iron shield.

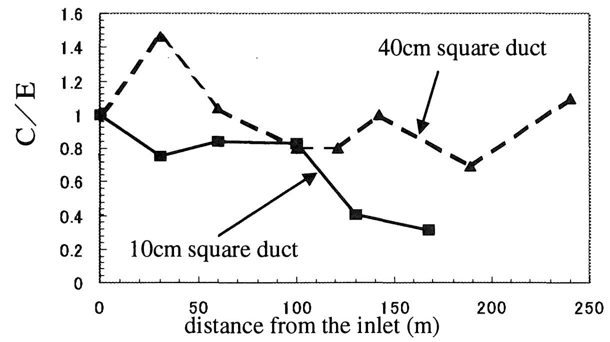

Fig. 5 Comparison of relative dose rates by this formula with experimental values in one stage 90-degree square bent duct with 10cm- and 40cm-side in polyethylene shield

15 cm. The other of the two-bent ducts was a large aperture square duct with 90-degree bend angles and 1.8m side. The one-bent ducts were aperture square ducts with 10cm, 20cm and 40cm sides. Comparing values by the simplified formula with experimental values of these ducts, the following conclusions were obtained.

1) For 45-degree bent duct with medium radius of 15 cm in gamma-ray source, the estimated dose rates agreed with experimental ones within 30% at every bend and were less than factor 2 at the exit.
2) For 90-degree bent square duct with 1.8 m side in gamma-ray source, the estimated dose rates agreed with the experimental ones within 30% at every bend point and at the exit for the anisotropic approximation. The approximation of $f_n = cos(\theta_n/2)$ gave a good approximation.
3) For 90-degree one-time bent square ducts with 10cm, 20cm and 40cm sides in iron and polyethylene shields with 14 MeV neutron source, roughly speaking, dose rates by the present simple formula agree with experimental values within factor 3 at the exit.
4) The present streaming formula derived by the optics analogy together with restricting where the streaming components have a main contribution to the dose rate. The formula can be applied as a tool in the midway of shielding design for near 1MeV gamma-ray and fusion neutron with 14 MeV energy.
5) On the other hand several points to be improved can be found in this work, and we must investigate to modify the simplified formula.

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