

Model Validation for Deposition on Unprotected Personnel

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Background

A model for the prediction of the surface deposition onto the human form has been developed, which incorporates local transport effects attributable to droplet mass (or, size) as well as other processes such as aerodynamic drag. The calculations required to determine the trapping efficiency of the human form for a given challenge aerosol concentration are described in the notebook entitled “Determination of Deposition Probability on the Human Form”. In this note, this model is applied to some system-level experimental data for deposition onto the unprotected human form that has been acquired in a wind-tunnel test. The test was conducted by Research Triangle Institute (RTI) and involved a full-scale aerosol challenge test on unprotected human (control ensemble). The human subject wore only a gas mask, boxer shorts and socks and combat boots.

Challenge aerosol

The challenge aerosol used for the deposition study is a tagged silica powder. The human test subject was exposed to a constant concentration of $C = 153.0769 \text{ mg } m^{-3}$ for a total exposure duration of 6.5 min, giving a total challenge of $Ct = 995 \text{ mg-min } m^{-3}$. The particle size distribution for the challenge aerosol was found to be approximately lognormal with a mass median diameter $\mu_{MMD} = 2.8 \text{ } \mu\text{m}$ and a geometric standard deviation of $\sigma_g = 2.3$.

(* Total aerosol challenge in mg-min m^{-3} *)

$Ct = 995.;$

(* Parameters of lognormal distribution describing
particle size distribution of challenge aerosol *)

$\mu_{MMD} = 2.8;$ (* MMD in μm *)

$\sigma_g = 2.3;$ (* geometric standard deviation *)

The functional form of the lognormal distribution $LN(\mu, \sigma)$ describing particle size distribution is given by:

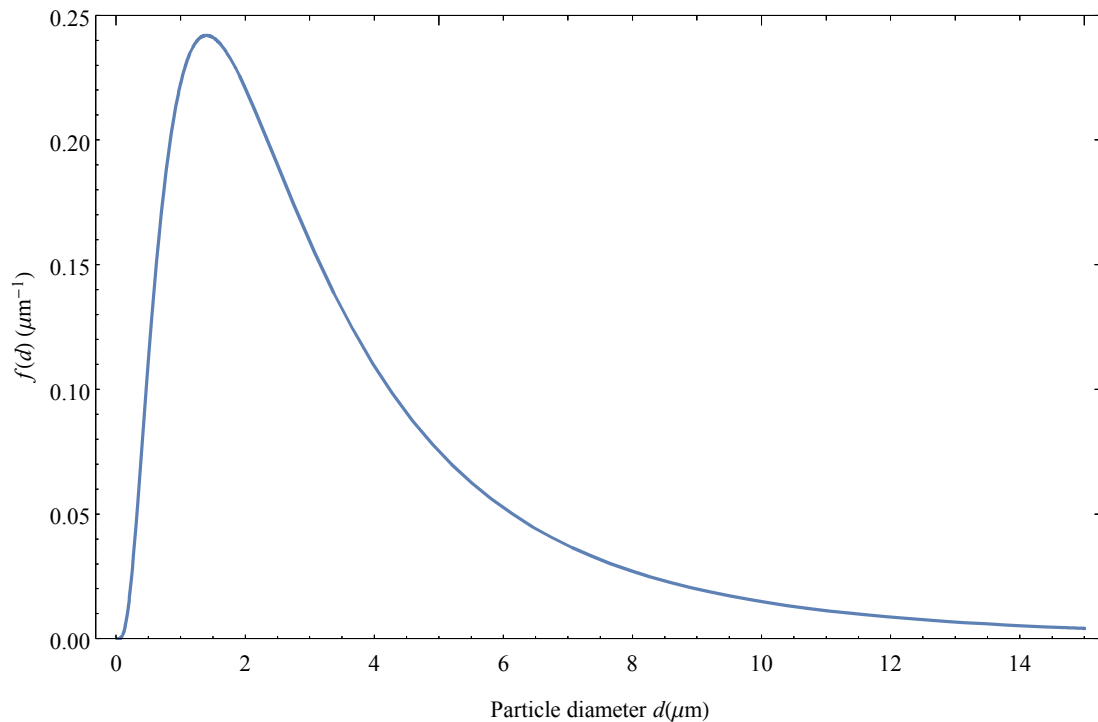
```
(*  $\mu$  and  $\sigma$  are the location and scale parameters of lognormal distribution;
d is the particle diameter *)
f[d_] = PDF[LogNormalDistribution[ $\mu$ ,  $\sigma$ ], d]

$$\begin{cases} \frac{e^{-\frac{(\ln d - \mu)^2}{2\sigma^2}}}{d\sqrt{2\pi}\sigma} & d > 0 \\ 0 & \text{True} \end{cases}$$


(* Location and scale parameters for particle size distribution associated with
challenge aerosol used in wind-tunnel experiment conducted by RTI *)

 $\mu = \text{Log}[\mu_{\text{MMD}}];$ 
 $\sigma = \text{Log}[\sigma_g];$ 

(* Plot the form of the particle size distribution for challenge aerosol *)
Plot[Evaluate[f[d]], {d, 0.01, 15.0},
BaseStyle → {FontFamily → "Times", 12},
Frame → True,
AxesOrigin → {0, 0},
PlotRange → {0, 0.25},
FrameLabel → {"Particle diameter  $d(\mu\text{m})$ ", " $f(d) (\mu\text{m}^{-1})$ "}, ImageSize → Large]
```



Sampling Locations on Human Form

Fifty-two locations on the human subject's skin were sampled in the wind-tunnel test conducted by RTI. These locations included the head, neck, torso, arms, legs, feet and hands. From this analysis, the rate

of aerosol deposition on the human subject's skin was summarized in terms of an aerosol deposition velocity v_d defined as follows:

$$v_d = (\text{Mass of deposited aerosol}) / (\text{Sample area} \times C_m \times T) ,$$

where C_m is the aerosol mass concentration (in mg m^{-3}) and T is the sample duration (in min). Normally, v_d is measured in cm min^{-1} .

Deposition velocity data for unprotected human

```
(* Deposition velocity (cm min-1) obtained from wind-
tunnel experiment conducted by RTI *)

v_d = {2.326, 12.710, 5.401, 22.456, 9.526, 9.171,
      8.344, 12.198, 1.249, 3.739, 87.800, 0.913, 0.492, 18.379, 0.105};

(* The deposition velocities contained in
list v_d correspond to the following body regions *)

bodyRegion = {
  "Head only (1,2R,2L)",
  "Neck only (3a,b,c,d,e,f,g)",
  "Front of neck (3a,b,c,d)",
  "Back of neck (3e,f,g)",
  "Chest (4,5,6)",
  "Back (29,30,31,32,33)",
  "Torso (4-8,29-33,42,43)",
  "Arm (11,13,34,35)",
  "Upper leg (14,15,16,18,36)",
  "Lower leg (20-25,38,39)",
  "Ear lobes (44R,44L)",
  "Scrotum (45)",
  "Ankles (47,50)",
  "Hands and wrists (55,56,58,62)",
  "Feet (48,53)"};

(* Construct table summarizing measurements of deposition
velocity on various body regions for unprotected human subject *)

(* Header labels for table *)

colLabels = Style[#, Bold] & /@
  {"Array Index", "Body Region", "Deposition Velocity (cm min-1)"};

(* Data for table *)
```

```
Grid[Join[{colLabels}, {Range[Length[bodyRegion]], bodyRegion, vd}],
  Dividers → {{1 → True, 2 → True, 3 → True, 4 → True}, {1 → True, 2 → True, -1 → True}},
  Alignment → Center,
  Spacings → {4.5, 0.5}]
```

Array Index	Body Region	Deposition Velocity (cm min ⁻¹)
1	Head only (1,2R,2L)	2.326
2	Neck only (3a,b,c,d,e,f,g)	12.71
3	Front of neck (3a,b,c,d)	5.401
4	Back of neck (3e,f,g)	22.456
5	Chest (4,5,6)	9.526
6	Back (29,30,31,32,33)	9.171
7	Torso (4-8,29-33,42,43)	8.344
8	Arm (11,13,34,35)	12.198
9	Upper leg (14,15,16,18,36)	1.249
10	Lower leg (20-25,38,39)	3.739
11	Ear lobes (44R,44L)	87.8
12	Scrotum (45)	0.913
13	Ankles (47,50)	0.492
14	Hands and wrists (55,56,58,62)	18.379
15	Feet (48,53)	0.105

Model Predictions of Deposition on Unprotected Human Form

The predicted distribution of the deposition density on the unprotected human form was obtained from the Fortran 90/95 program challengeGV4.f90 which uses the distribution of shear velocity on human form to determine the deposition velocity and the subsequently the deposition probability. From the deposition density on the human form, the mass deposition on different parts of the human body can be determined.

First, we read in data set summarizing the prediction of the aerosol deposition on the unprotected human form for the challenge aerosol used in the wind-tunnel tests conducted by RTI. This data set was produced by the challengeGV4 program. The data set consists of three columns: (1) body part index (1:11), (2) deposited mass on the body part (in mg), and (3) fractional deposition on body part [-].

```

dep =
  Import["C:\\Deposition on Humans Project\\Challenge Levels\\Validation\\Naked
    Man - using ustar data\\0 deg\\massDep-NakedMan-U-Reduced.dat", "Table"]
{{1, 11.6042, 0.0626581}, {2, 2.75904, 0.0148977},
 {3, 9.58522, 0.0517562}, {4, 15.0513, 0.0812707}, {5, 24.9103, 0.134505},
 {6, 8.48462, 0.0458134}, {7, 67.0062, 0.361806}, {8, 7.22719, 0.0390238},
 {9, 19.6984, 0.106363}, {10, 12.733, 0.0687527}, {11, 6.14, 0.0331535}}

```

```

(* Extract mass deposition on body parts in mg *)
massDeposited = dep[[All, 2]];

```

The area of the body parts for the computerized mannikin are given below (in m^2). The body part indices are as follows:

- 1 - head (entire)
- 2 - neck (entire)
- 3 - upper chest (including shoulders and down to just below the nipples)
- 4 - lower abdomen (including stomach and down to waist)
- 5 - arms (left and right)
- 6 - hands (left and right)
- 7 - legs (left and right, front and back)
- 8 - feet (left and right)
- 9 - back
- 10 buttocks
- 11 crotch area (frontal area below the waist)

```

(* Areas of body parts of computerized mannikin in m2 *)
areaBodyPart = {0.1137, 0.027016, 0.09386, 0.1474,
  0.2438, 0.08314, 0.6601, 0.1027, 0.1930, 0.1248, 0.0601};

(* The total body surface area in m2 *)
totalBodyArea = Total[areaBodyPart];

```

Comparison of Predictions with Measurements

Given the measured deposition velocities obtained in the wind-tunnel experiment conducted by RTI, we can convert these deposition velocities into mass of challenge aerosol deposited on various body regions and compare this with model predictions (see previous section).

Measured mass deposited on various body regions

The mass deposited in various body regions will be accumulated in the list measuredMass.

```
(* Mass deposited on neck in mg - samples 3a,b,c,d,e,f,
g compared with predicted mass deposited on body part index 2 *)

measuredMass = {v_d[[2]] areaBodyPart[[2]] Ct 1 / 100.};
(* 1/100. is used to convert from cm to m *)

(* Mass deposited on upper chest - samples 4,5,
6 compared with predicted mass deposited on body part 3 *)

AppendTo[measuredMass, v_d[[5]] areaBodyPart[[3]] Ct 1 / 100.];

(* Mass deposited on back - samples 29,30,31,32,
33 compared with predicted mass deposited on body part 9 *)

AppendTo[measuredMass, v_d[[6]] areaBodyPart[[9]] Ct 1 / 100.];

(* Mass deposited on arms - samples 11,13,34,
35 compared with predicted mass deposited on body part 5 *)

AppendTo[measuredMass, v_d[[8]] areaBodyPart[[5]] Ct 1 / 100.];

(* Mass deposited on hands - samples 55,56,58,
62 compared with predicted mass deposited on body part 6 *)

AppendTo[measuredMass, v_d[[14]] areaBodyPart[[6]] Ct 1 / 100.];

(* Mass deposited on lower portion of body below waist,
excluding feet - samples 14-18,20-25,36,38,
39 compared with predicted mass deposited on body parts 7,10, and 11 *)

AppendTo[measuredMass, 0.5 (v_d[[9]] + v_d[[10]]
  (areaBodyPart[[7]] + areaBodyPart[[10]] + areaBodyPart[[11]]) Ct 1 / 100.);

(* Mass deposited on torso - samples 4-8,29-33,42,
43 compared with predicted mass deposited on body parts 3, 4, and 9 *)

AppendTo[measuredMass,
  v_d[[7]] (areaBodyPart[[3]] + areaBodyPart[[4]] + areaBodyPart[[9]]) Ct 1 / 100.);
```

Comparison

```
(* Construct table that can be used to compared the measured mass
deposition with the predicted mass deposition in various body regions *)

dataCompare = {measuredMass, Join[massDeposited[{2, 3, 9, 5, 6}],
  {massDeposited[[7]] + massDeposited[[10]] + massDeposited[[11]],
  massDeposited[[3]] + massDeposited[[4]] + massDeposited[[9]]}] };
```

```

region = {
  "Neck",
  "Upper chest",
  "Back",
  "Arms",
  "Hands",
  "Below waist excluding feet",
  "Torso"};

bodyIndexCompared = {
  "2",
  "3",
  "9",
  "5",
  "6",
  "(7+10+11)",
  "(3+4+9)"};

totalData = Table[Join[Join[{bodyIndexCompared, region}^T][[i]], dataCompare[[i]]],
  {i, Length[dataCompare]}];

colLabels1 = Style[#, Bold] & /@
  {"Body Index", "Body Region", "Measured (mg)", "Predicted (mg)"};

(* Construct table comparing measured deposition
   on body parts with predicted deposition on body parts *)

Grid[Join[{colLabels1}, totalData],
  Dividers →
    {{1 → True, 2 → True, 3 → True, 4 → True, 5 → True}, {1 → True, 2 → True, -1 → True}},
  Alignment → Center,
  Spacings → {3.5, 0.5}]

```

Body Index	Body Region	Measured (mg)	Predicted (mg)
2	Neck	3.41656	2.75904
3	Upper chest	8.8964	9.58522
9	Back	17.6115	19.6984
5	Arms	29.59	24.9103
6	Hands	15.2039	8.48462
(7+10+11)	Below waist	20.9689	85.8792
	excluding feet		
(3+4+9)	Torso	36.0535	44.3349

Comments: The greatest deviation is in body region below the waist excluding the feet, where the predicted and measured deposition differ by roughly a factor of four. However, this discrepancy may be due to the fact that this body region for the human subject in the wind-tunnel tests was covered to a certain extent (viz., the human test subject wore boxer shorts that extended almost to the knees and socks and combat boots that extended almost up to the calves which provided some protection). The

predicted deposition was for a completely nude human subject. Another way of looking at this is that the limited clothing worn by the human test subject in the body region below the waist provided a protection factor of about four with respect to this body region.