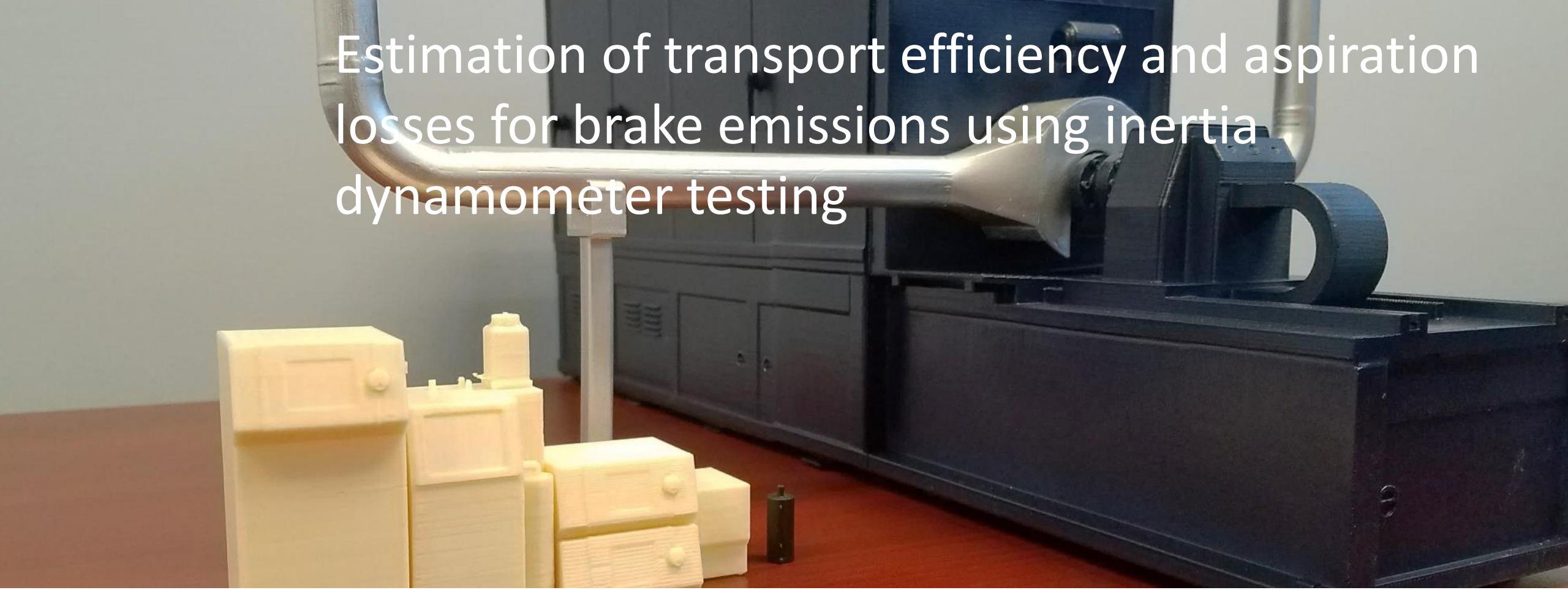


Estimation of transport efficiency and aspiration losses for brake emissions using inertia dynamometer testing

Carlos Agudelo, Ravi Vedula, and Tyler Odom

47th PMP meting, May 16-17, 2018

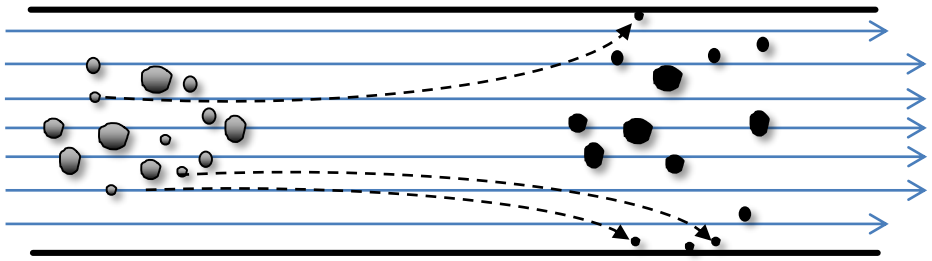
dominant losses
main variables
brake dyno testing

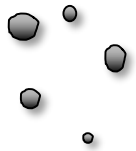
~6 nm

10 µm

diffusion losses

tendency of smaller particles to migrate to lower concentration regions



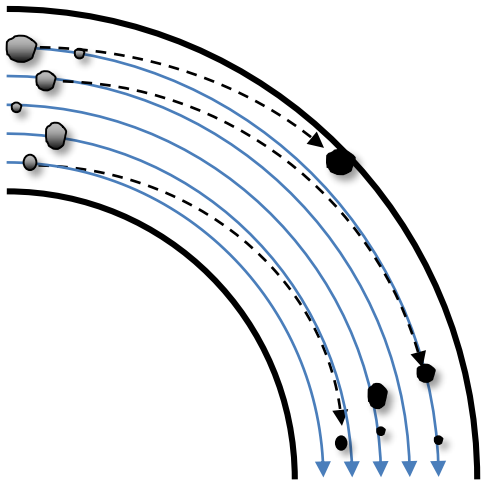


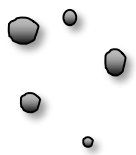
inlet

outlet

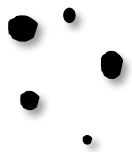
inertial deposition in bends

tendency of larger particles to deviate from the air flow path





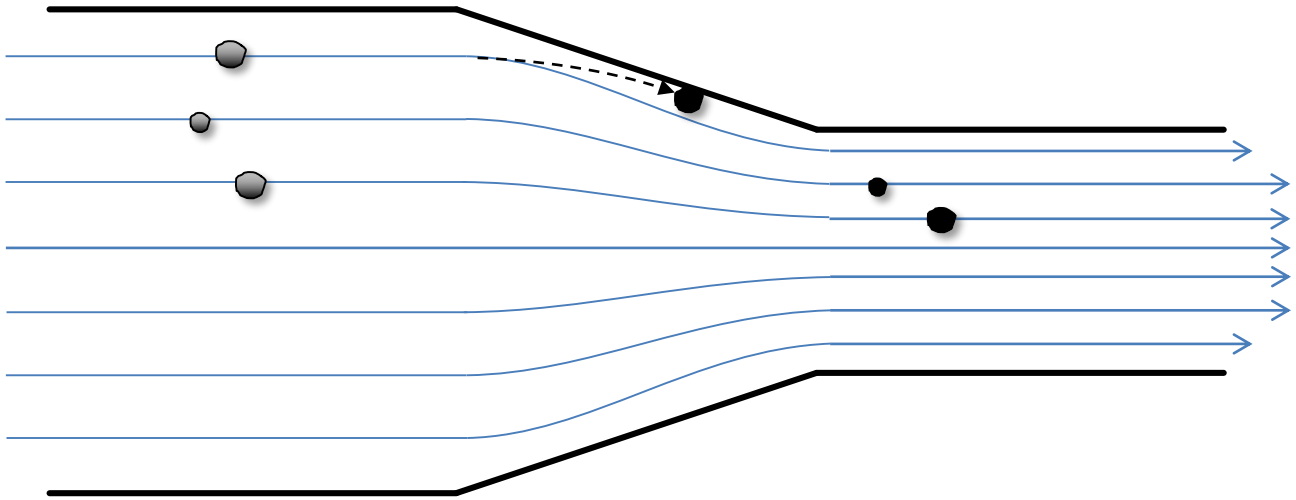
inlet

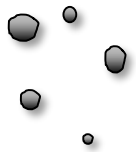


outlet

contraction losses

tendency of larger particles to deviate from flow lines and adhere to the walls



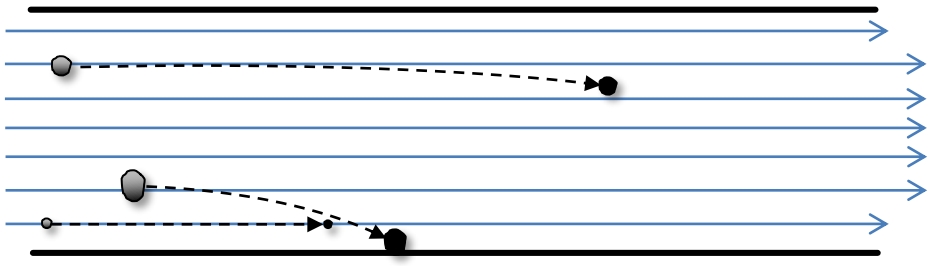


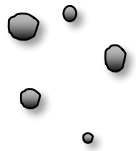
inlet

outlet

gravitational losses

tendency of larger particles to deposit on lower walls for non-vertical ducts



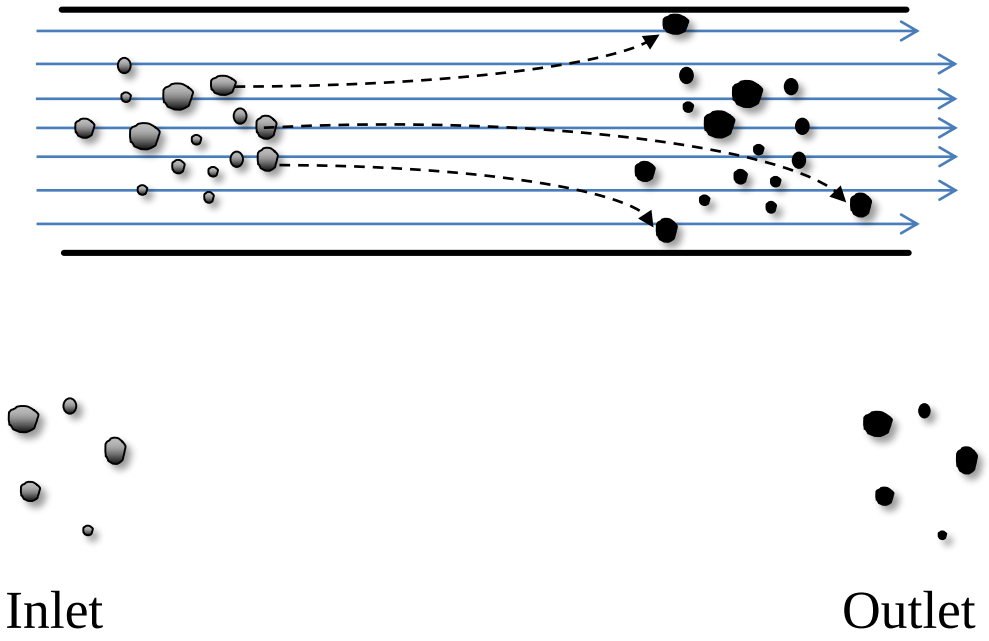


inlet

outlet

turbulent deposition losses

tendency of medium-to-large particles to migrate to less turbulent regions



CENTERS FOR DISEASE CONTROL AND PREVENTION

MAX-PLANCK-GESELLSCHAFT

AC –
Aerosol Calculator
Paul Baron

PLC –
Particle Loss
Calculator

SAE AIR6504:2017
non-volatile
PM losses

humid air density

	LINK	CDC Centers for Disease Control and Prevention	Max-Planck-Gesellschaft	SAE
air pressure	☑	☑	☑	☑
air temperature	☑	☑	☑	☑
relative humidity	☑			
lab site elevation	☑			
duct pressure	☑			
sampling vacuum	☑			
particle density*	☑			

*using skeletal or constituent density as a function of particle size

humid air density calculation

laboratory elevation, air temperature, relative humidity, and system's pressure determine the air density in the duct and the sampling line

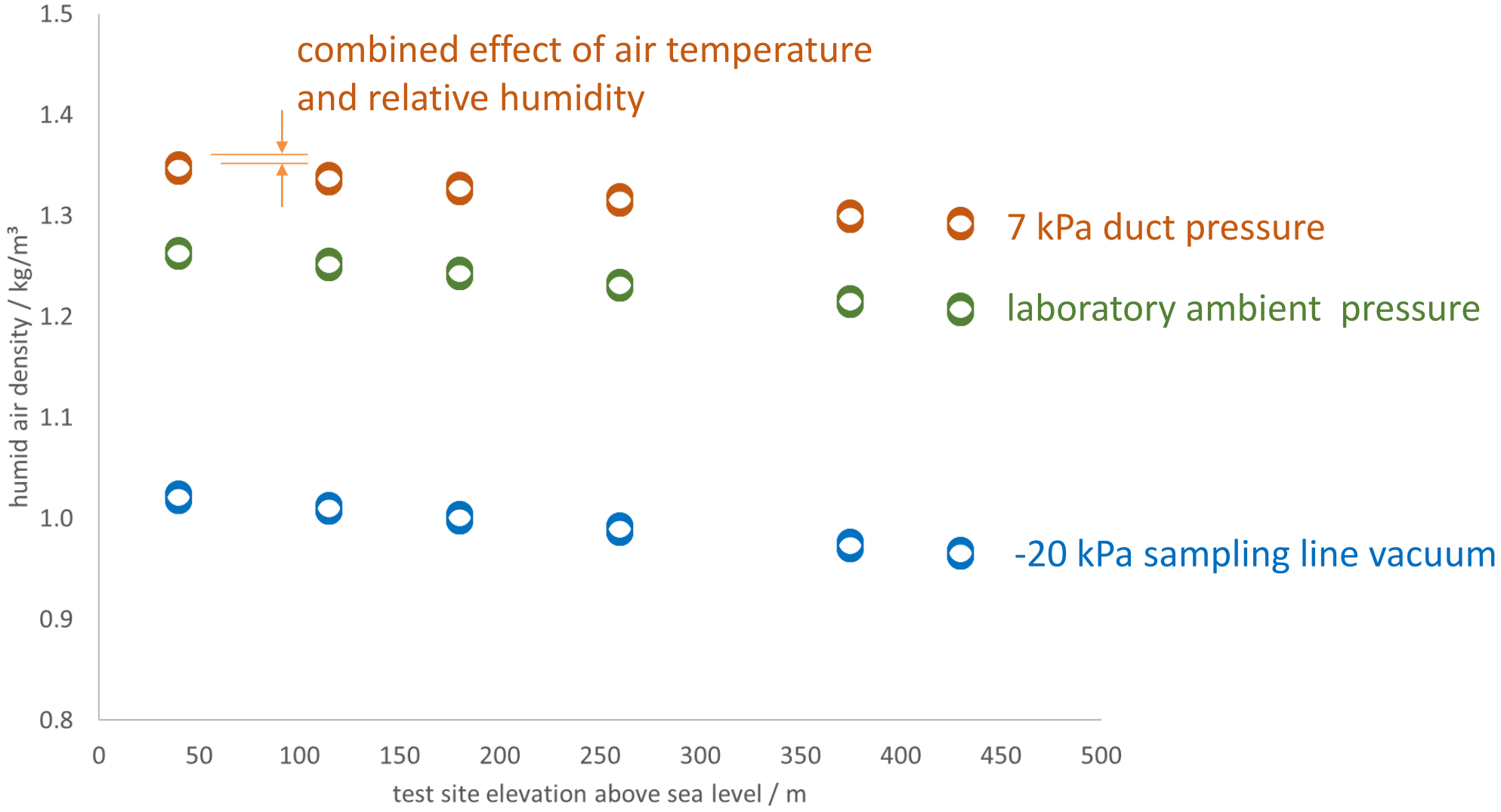
Location	elevation / m
Cologne, LA, Seoul, Shanghai, Tokyo	40
Frankfurt/Milan	115
Detroit/Prague	180
Stuttgart	260
Ingolstadt	375
Varese	430

	Rel Hum. / %RH	Air temp. / °C	Syst. Press / kPa
Low/minimum	50	15	-
Average	60	20	3.5
High/maximum	70	25	7.0

Location	elevation / m	Rel Hum. / %RH	Air temp. / °C	psat / kPa	p / kPa	pv / kPa	pd	$\rho_{humid\ air}$ / kg/m³
Cologne, LA, Seoul, Shanghai, Tokyo / 0	40	50	15	1.71	100.8	0.85	100.0	1.215
Cologne, LA, Seoul, Shanghai, Tokyo / 3.5	40	50	15	1.71	104.3	0.85	103.5	1.258
Cologne, LA, Seoul, Shanghai, Tokyo / 7	40	50	15	1.71	107.8	0.85	107.0	1.300
Frankfurt/Milan / 0	115	50	15	1.71	100.0	0.85	99.1	1.205
Frankfurt/Milan / 3.5	115	50	15	1.71	103.5	0.85	102.6	1.247
Frankfurt/Milan / 7	115	50	15	1.71	107.0	0.85	106.1	1.289
Detroit/Prague / 0	180	50	15	1.71	99.2	0.85	98.3	1.195
Detroit/Prague / 3.5	180	50	15	1.71	102.7	0.85	101.8	1.238
Detroit/Prague / 7	180	50	15	1.71	106.2	0.85	105.3	1.280
Stuttgart / 0	260	50	15	1.71	98.2	0.85	97.4	1.184
Stuttgart / 3.5	260	50	15	1.71	101.7	0.85	100.9	1.226
Stuttgart / 7	260	50	15	1.71	105.2	0.85	104.4	1.268
Ingolstadt / 0	375	50	15	1.71	96.9	0.85	96.0	1.168
Ingolstadt / 3.5	375	50	15	1.71	100.4	0.85	99.5	1.210
Ingolstadt / 7	375	50	15	1.71	103.9	0.85	103.0	1.252
Varese / 0	430	50	15	1.71	96.3	0.85	95.4	1.160
Varese / 3.5	430	50	15	1.71	99.8	0.85	98.9	1.202
Varese / 7	430	50	15	1.71	103.3	0.85	102.4	1.245

humid air density variation

duct (positive) or sampling line (vacuum) pressure, followed by lab elevation, are the dominant factors to determine the humid air density



type of loss

	LINK	CDC Centers for Disease Control and Prevention	Max-Planck-Gesellschaft	SAE
diffusion – laminar	☑	☑	☑	
diffusion – turbulent	☑	☑	☑	☑
bends	☑	☑	☑	☑
constriction	☑	☑	☑	
gravitational	☑	☑	☑	
inertial deposition	☑	☑	☑	
isokinetic aspiration	☑	☑	☑	
isokinetic with lip effect	☑			
isokinetic gravitational	☑	☑		
isokinetic - inertial	☑	☑		
model averaging	☑			

main parameter entry and models selection

particle size, particle density, duct diameter, airflows and models to iterate

Inertia Brake Dynamometer Particle Sampling Efficiency
Macro v1.0.0 - user input and equations

Run Macro

equation # iteration parameters - particle and system size

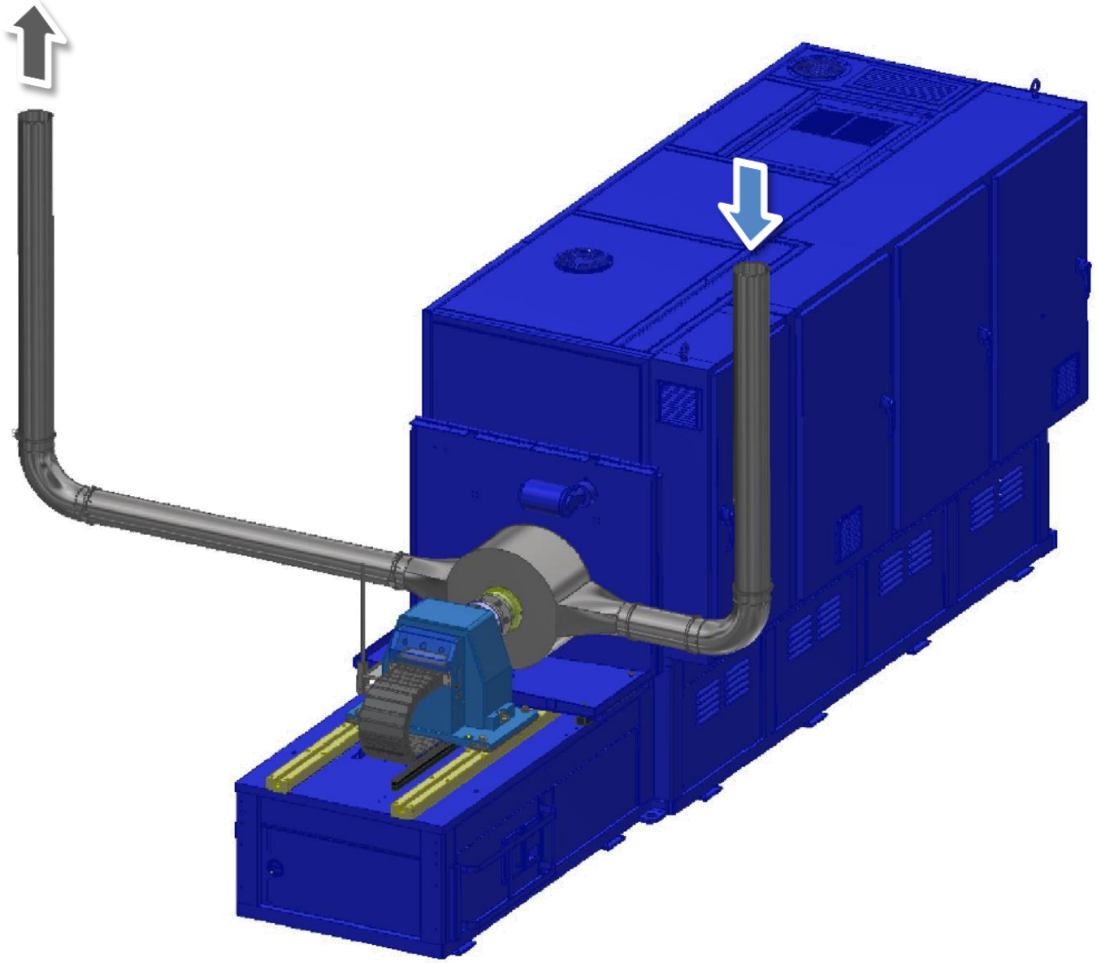
particle diameter	0.0055	0.01	0.015	0.025	0.032
particle density	3000	3000	3000	3000	3000
duct diameter	150	250			
airflow	250	400	600	1000	1500
sampling flow	15	30			

	iteration parameters - efficiency model	**execute**
Model1	AC	Yes
Model2	SAE	Yes
Model3	PLC	Yes
Model4	LINK-II	Yes
Average	LINK-I	Yes

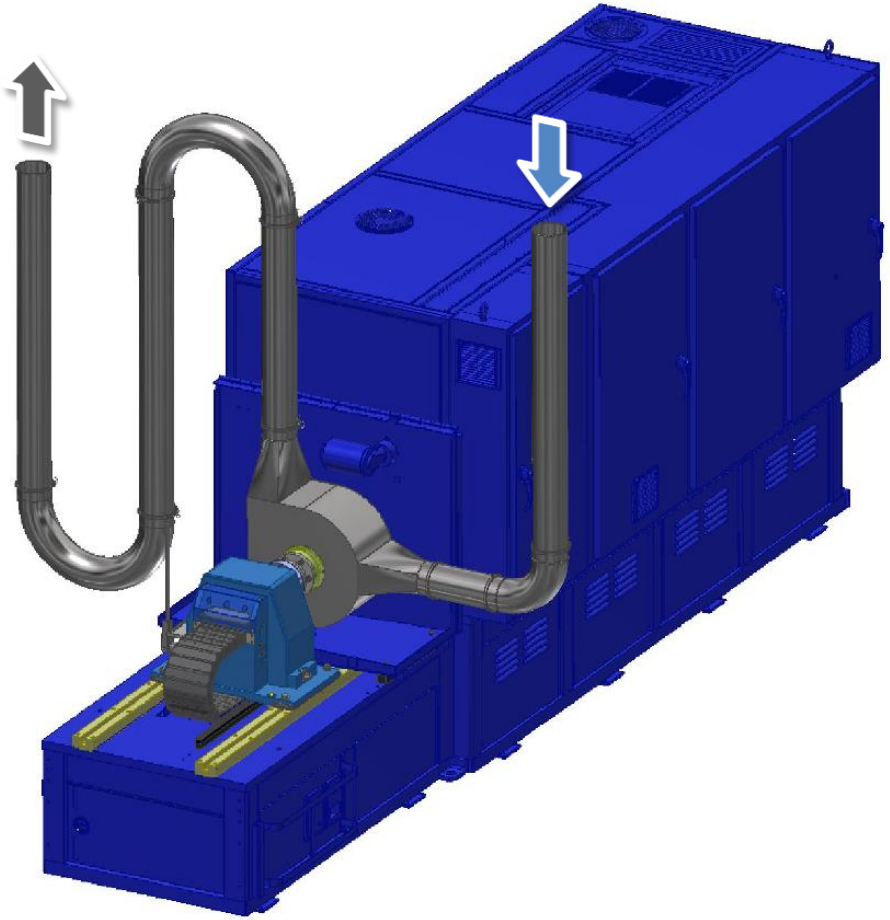
Number of different losses to average **20**

two duct layouts (examples)

actual configuration and size also considers lab/dyno space and instrumentation cluster, round enclosure, post fixture, and sampling points per EPA Method 1A



Layout A

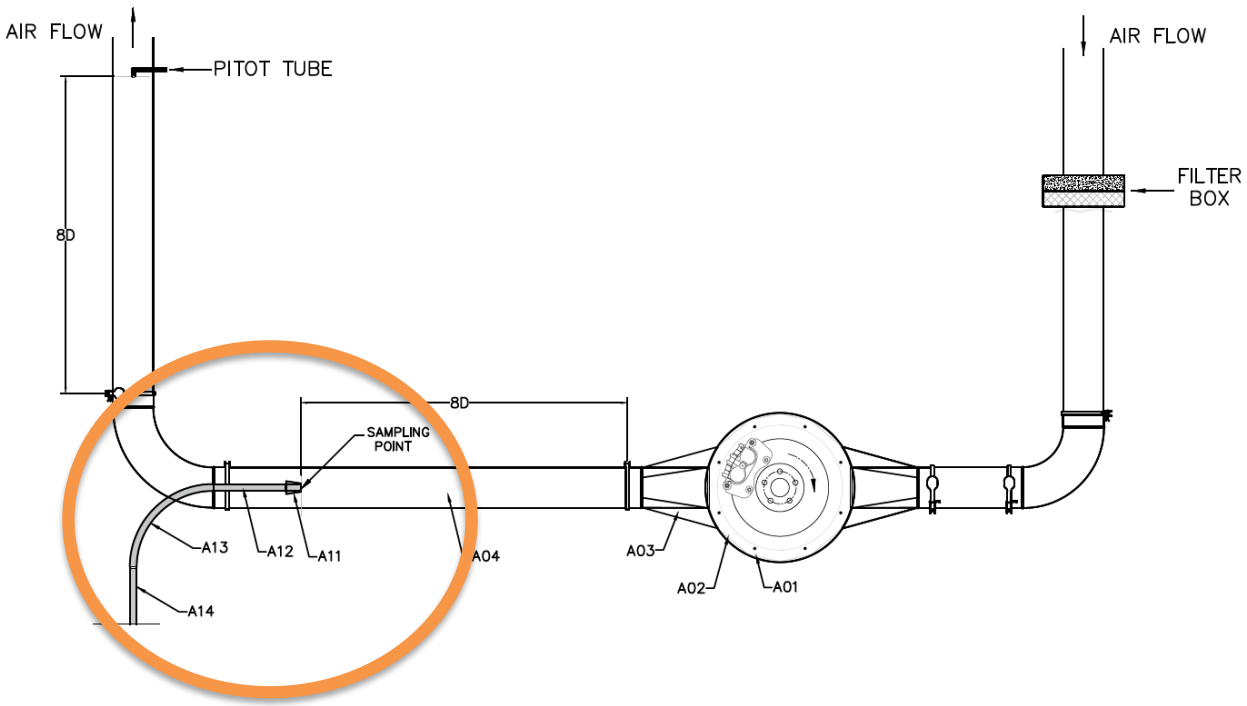


Layout B

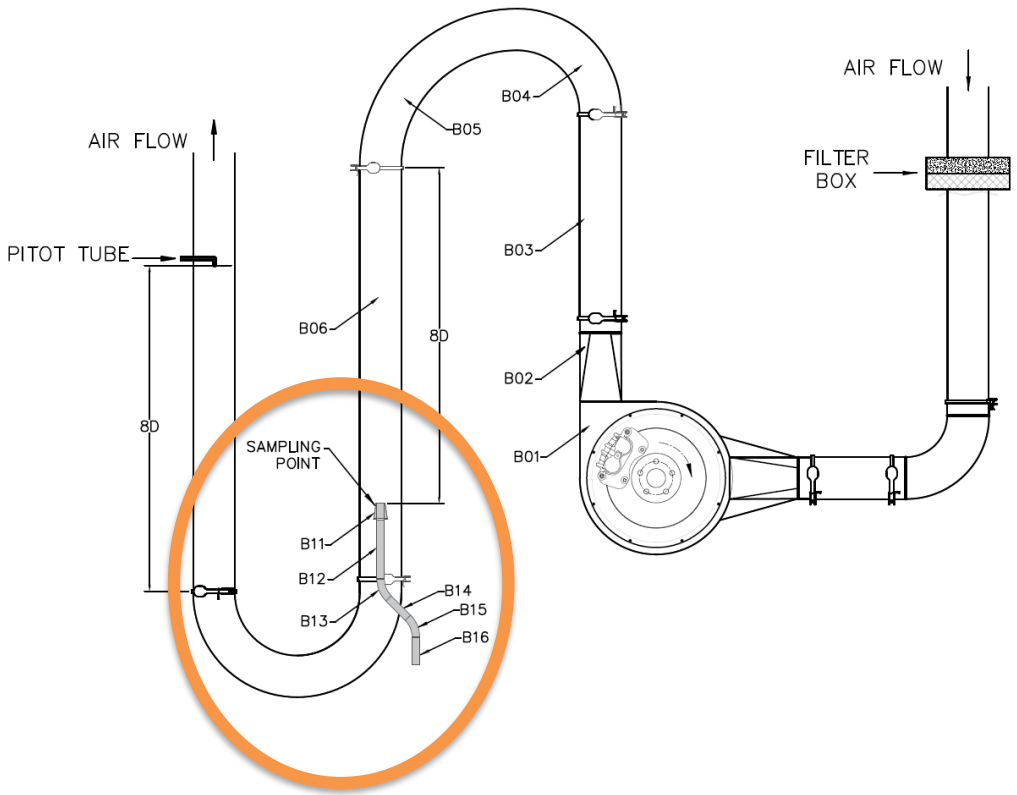
two sampling lines layouts

sampling efficiency is sensitive to nozzle size, line diameter, layout, and lengths

layout B is less sensitive to size and layout (mostly vertical, with smooth bends)



Layout A



Layout B

sectors and air parameters

parameter entries for sector description and cooling air conditions

Inertia Brake Dynamometer Particle Sampling Efficiency Macro v1.0.0 - user input and equations

Run Macro

iteration parameters - layout						
section		A	A	A	A	A
		duct	duct	duct	duct	s/line
sector		01	02	03	04	11
code		A01	A02	A03	A04	A11
description		encl constr.	encl constr.	trans constr.	8D	nozz
orientation		horz.	horz.	horz.	horz.	horz.
include (yes/no) for layout selection		**No**	**No**	**No**	**No**	**No**
iteration parameters - math input						
air	STPH					
temperature	20	20	20	20	20	20
temperature		293.15	293.15	293.15	293.15	293.15
RH	50	50	50	50	50	50
air pressure above sea level in Michigan, US		97.78	97.78	97.78	97.78	97.78
actual pressure	101.325	101.28	101.28	101.28	101.28	77.28
air density		1.233	1.233	1.233	1.233	0.945

parameters for each sector

data entry with dimensions for each sector of duct and sampling lines

iteration parameters - math input

enclosure and constriction

	mm	entry Z dim	300.0	300.0	300.0
	mm	entry Y dim	558.0	507.0	308.0
	mm	exit Z dim	300.0	300.0	150.0
	mm	exit Y dim	507.0	308.0	150.0
	mm	entry hydraulic dia	390.2	377.0	303.9
	mm	exit hydraulic dia	377.0	303.9	150.0
	mm	length (X dim)	116.0	116.0	287.0

round duct

	mm	duct diameter	150.0
$R_{o,d}$	-	bend curvature ratio	
$\theta_{b,d}$	deg	bend angle	
$L_{horz.,d}$	mm	projected horizontal length for bends	
	mm	height above ground level	
		straight duct (L/d) ratio	8.0
$L_{round,d}$	mm	length of sector	1200.0

Enter sampling dia and wall thickness in inches. =(dia-w.thick)*25.4 mm

sampling line

		nozzle diameter - exactly isokinetic? (*1 for yes/ 0 for no*)	1			
d_n	mm	isokinetic diameter	7.35			
	mm	If not isokinetic, enter nozzle inner diameter				
R	-	Else, enter isokineticity ratio (*desired range of 0.9 to 1.1*)				
d_s	mm	s/line diameter (*assuming 0.065" thick wall for 3/4" OD; 0.035" for 3/8" OD*)		8.6	8.6	8.6
$R_{o,s}$	-	bend curvature ratio			4.0	
$\theta_{b,s}$	deg	bend angle			90.0	
$L_{horz.,s}$	mm	projected horizontal length for bends			17.3	
L_s	mm	length of sector	29.4	20.0	27.1	120.0

tabular output

example of output table for models and equations pre-selected

model	code	description	orientation	duct diameter / mm	airflow / m³/h	sampling flow / l/min	equation	Legend	0.0055	0.01	0.1	1	2.5	10
AC	A15	nozz	horz.	150	250	40	net eff. nozz.	AC-A15-nozz-150-250-40-net eff. nozz.	100.00%	100.00%	99.97%	99.62%	98.61%	89.82%
PLC	A15	nozz	horz.	150	250	40	isok. asp. eff.	PLC-A15-nozz-150-250-40-isok. asp. eff.						100.00%
LINK-II	A15	nozz	horz.	150	250	40	net eff. nozz.	LINK-II-A15-nozz-150-250-40-net eff. nozz.	100.00%	100.00%	99.97%	99.62%	98.60%	89.77%
LINK-I	A15	nozz	horz.	150	250	40	isok. asp. eff.	LINK-I-A15-nozz-150-250-40-isok. asp. eff.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
AC	A15	nozz	horz.	150	400	40	net eff. nozz.	AC-A15-nozz-150-400-40-net eff. nozz.	100.00%	100.00%	99.97%	99.56%	98.41%	88.46%
PLC	A15	nozz	horz.	150	400	40	isok. asp. eff.	PLC-A15-nozz-150-400-40-isok. asp. eff.						100.00%
LINK-II	A15	nozz	horz.	150	400	40	net eff. nozz.	LINK-II-A15-nozz-150-400-40-net eff. nozz.	100.00%	100.00%	99.97%	99.56%	98.41%	88.41%
LINK-I	A15	nozz	horz.	150	400	40	isok. asp. eff.	LINK-I-A15-nozz-150-400-40-isok. asp. eff.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
AC	A15	nozz	horz.	150	600	40	net eff. nozz.	AC-A15-nozz-150-600-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
PLC	A15	nozz	horz.	150	600	40	isok. asp. eff.	PLC-A15-nozz-150-600-40-isok. asp. eff.					100.00%	100.00%
LINK-II	A15	nozz	horz.	150	600	40	net eff. nozz.	LINK-II-A15-nozz-150-600-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
LINK-I	A15	nozz	horz.	150	600	40	isok. asp. eff.	LINK-I-A15-nozz-150-600-40-isok. asp. eff.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
AC	A15	nozz	horz.	150	1000	40	net eff. nozz.	AC-A15-nozz-150-1000-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
PLC	A15	nozz	horz.	150	1000	40	isok. asp. eff.	PLC-A15-nozz-150-1000-40-isok. asp. eff.					100.00%	100.00%
LINK-II	A15	nozz	horz.	150	1000	40	net eff. nozz.	LINK-II-A15-nozz-150-1000-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
LINK-I	A15	nozz	horz.	150	1000	40	isok. asp. eff.	LINK-I-A15-nozz-150-1000-40-isok. asp. eff.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
AC	A15	nozz	horz.	150	1500	40	net eff. nozz.	AC-A15-nozz-150-1500-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
PLC	A15	nozz	horz.	150	1500	40	isok. asp. eff.	PLC-A15-nozz-150-1500-40-isok. asp. eff.					100.00%	
LINK-II	A15	nozz	horz.	150	1500	40	net eff. nozz.	LINK-II-A15-nozz-150-1500-40-net eff. nozz.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
LINK-I	A15	nozz	horz.	150	1500	40	isok. asp. eff.	LINK-I-A15-nozz-150-1500-40-isok. asp. eff.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

dominant losses per layout and sector

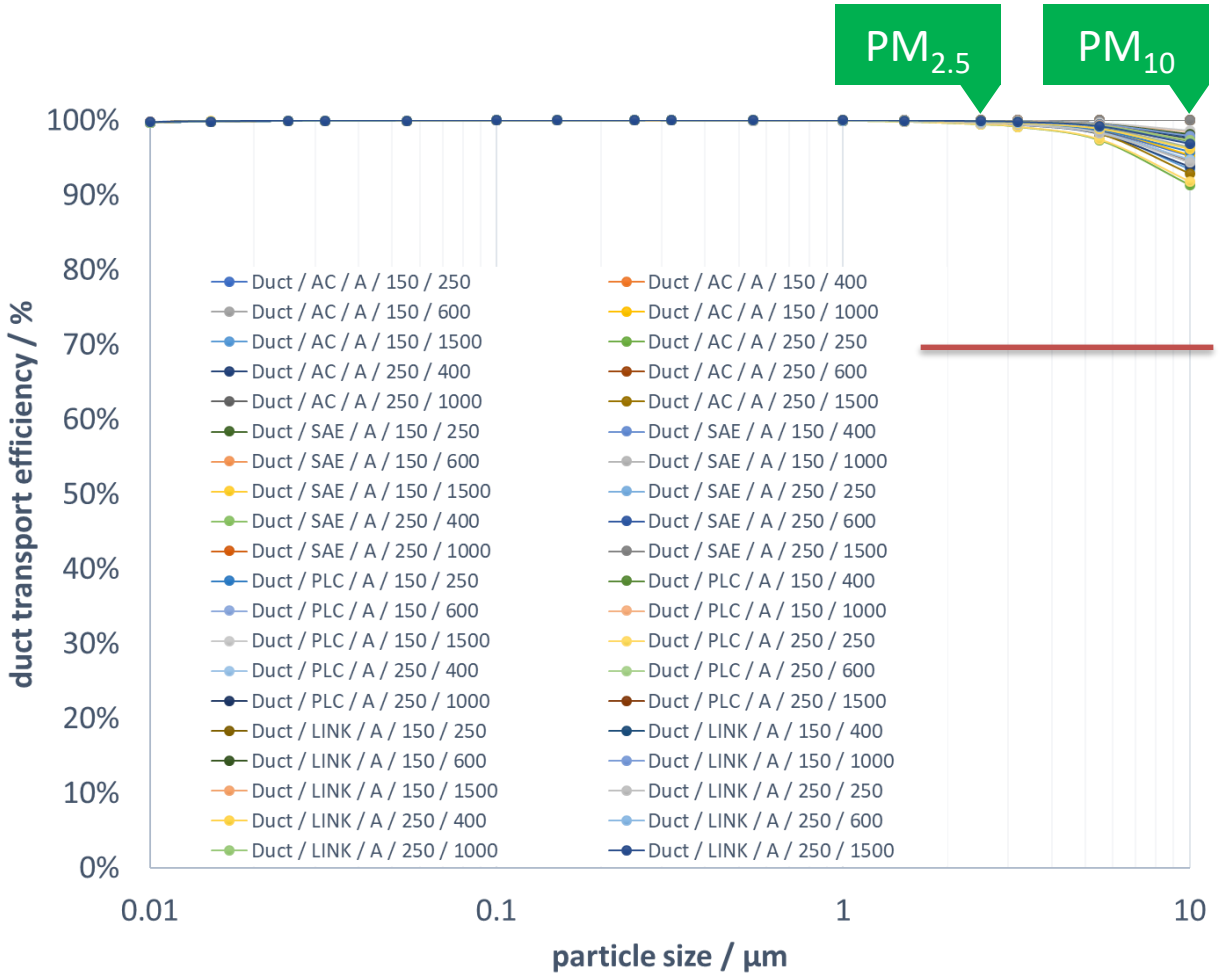
e.g.: layout A, 150-mm duct and 30 LPM sampling flow for PM10

duct airflow	aerosol loss type	layout A								layout B											
		01	02	03	04	11	12	13	14	01	02	03	04	05	06	11	12	13	14	15	16
400 m^3/h	diff. tran. eff.	100%	100%	100%	100%		100%	100%	100%	100%	100%	100%	100%	100%	100%		100%	100%	100%	100%	100%
	grav tran. eff.	100%	100%	99%	99%		97%	99%		99%			100%	100%				100%	94%	100%	
	iner. tran. eff.	100%	100%	100%	100%					100%	100%	100%	100%	100%	100%						
	contrac. tran. eff.	100%	100%	99%						100%	98%										
	bend tran. eff.							79%					89%	89%				93%		93%	
	net eff. w/o nozz.	100%	100%	99%	99%		98%	78%	100%	99%	99%	100%	89%	89%	100%		100%	92%	96%	92%	100%
	net eff. nozz. - lam					92%										100%					
600 m^3/h	diff. tran. eff.	100%	100%	100%	100%		100%	100%	100%	100%	100%	100%	100%	100%	100%		100%	100%	100%	100%	100%
	grav tran. eff.	100%	100%	100%	99%		97%	99%		99%			100%	100%				100%	94%	100%	
	iner. tran. eff.	100%	100%	100%	100%					100%	100%	100%	100%	100%	100%						
	contrac. tran. eff.	100%	100%	99%						100%	97%										
	bend tran. eff.							79%					85%	85%				93%		93%	
	net eff. w/o nozz.	100%	100%	99%	99%		98%	78%	100%	99%	99%	100%	85%	85%	100%		100%	92%	96%	92%	100%
	net eff. nozz. - lam					86%										100%					
1000 m^3/h	diff. tran. eff.	100%	100%	100%	100%		100%	100%	100%	100%	100%	100%	100%	100%	100%		100%	100%	100%	100%	100%
	grav tran. eff.	100%	100%	100%	99%		97%	99%		100%			100%	100%				100%	94%	100%	
	iner. tran. eff.	100%	100%	100%	100%					100%	100%	100%	100%	100%	100%						
	contrac. tran. eff.	100%	100%	98%						99%	95%										
	bend tran. eff.							79%					77%	77%				93%		93%	
	net eff. w/o nozz.	100%	100%	99%	100%		98%	78%	100%	99%	98%	100%	77%	77%	100%		100%	92%	96%	92%	100%
	net eff. nozz. - turb					84%										100%					

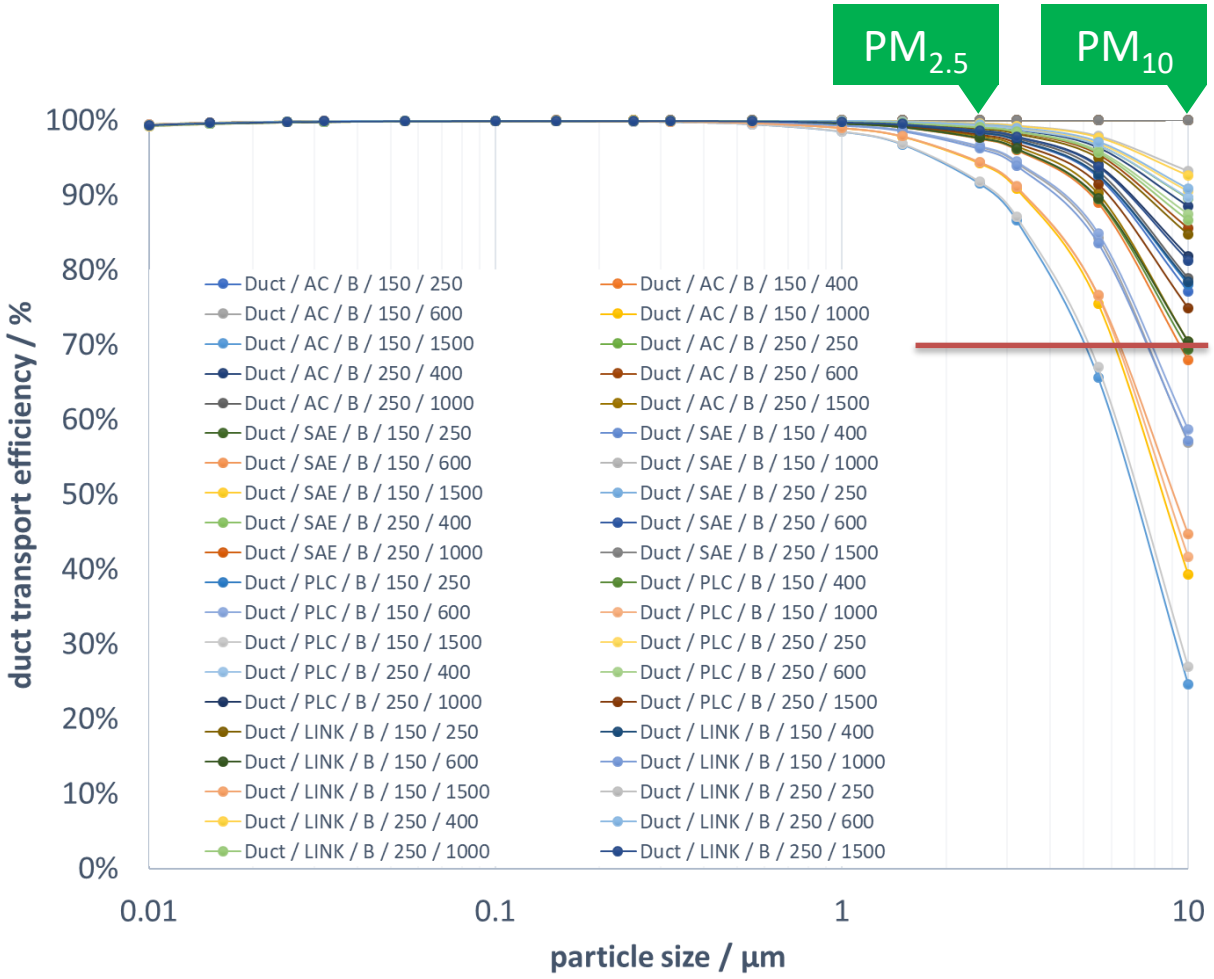
transport efficiency in the duct (prior to the nozzle)

layout A is less sensitive to duct diameter and air flow settings

layout B has efficiencies above 70% only for 250-mm duct size



Layout A

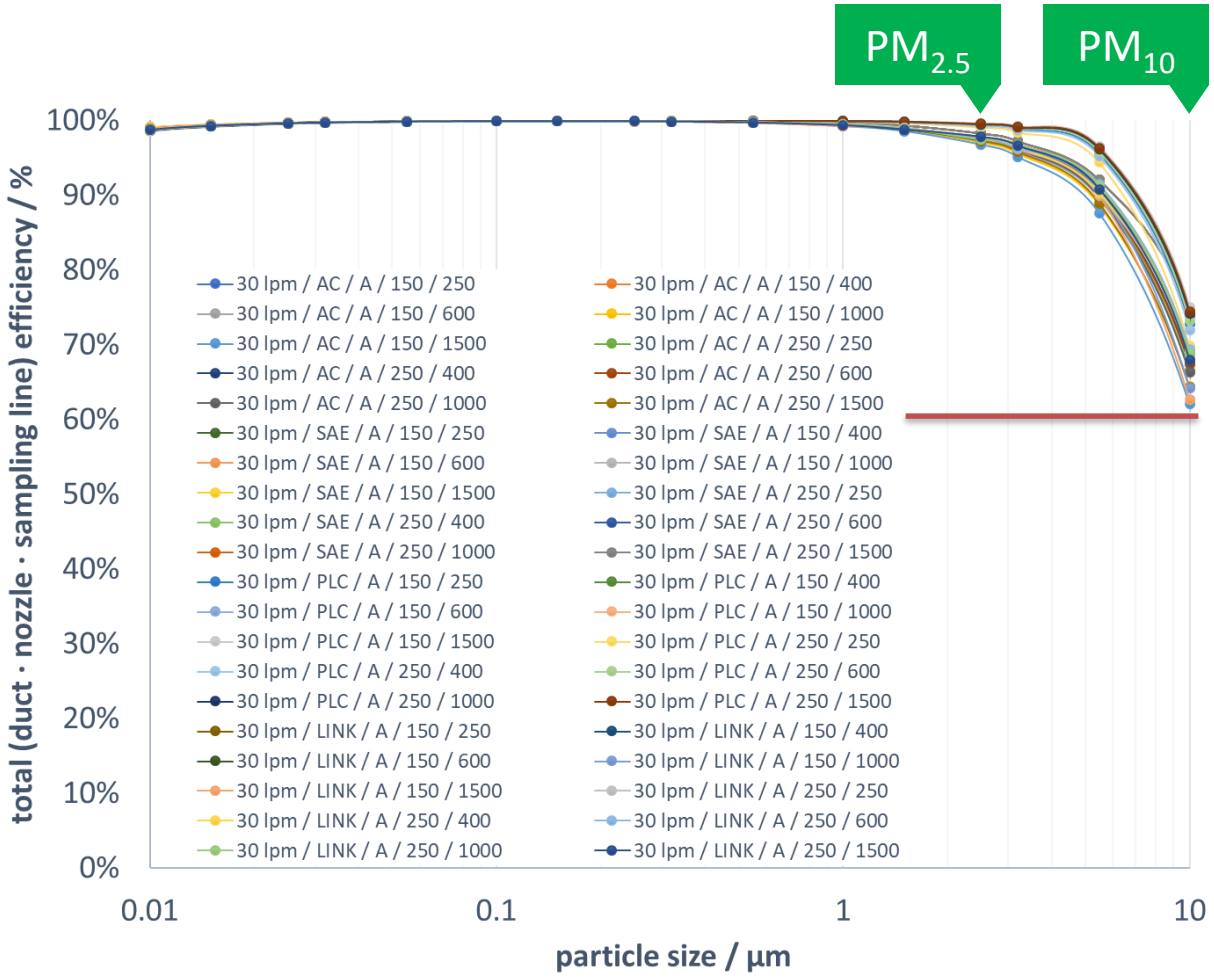


Layout B

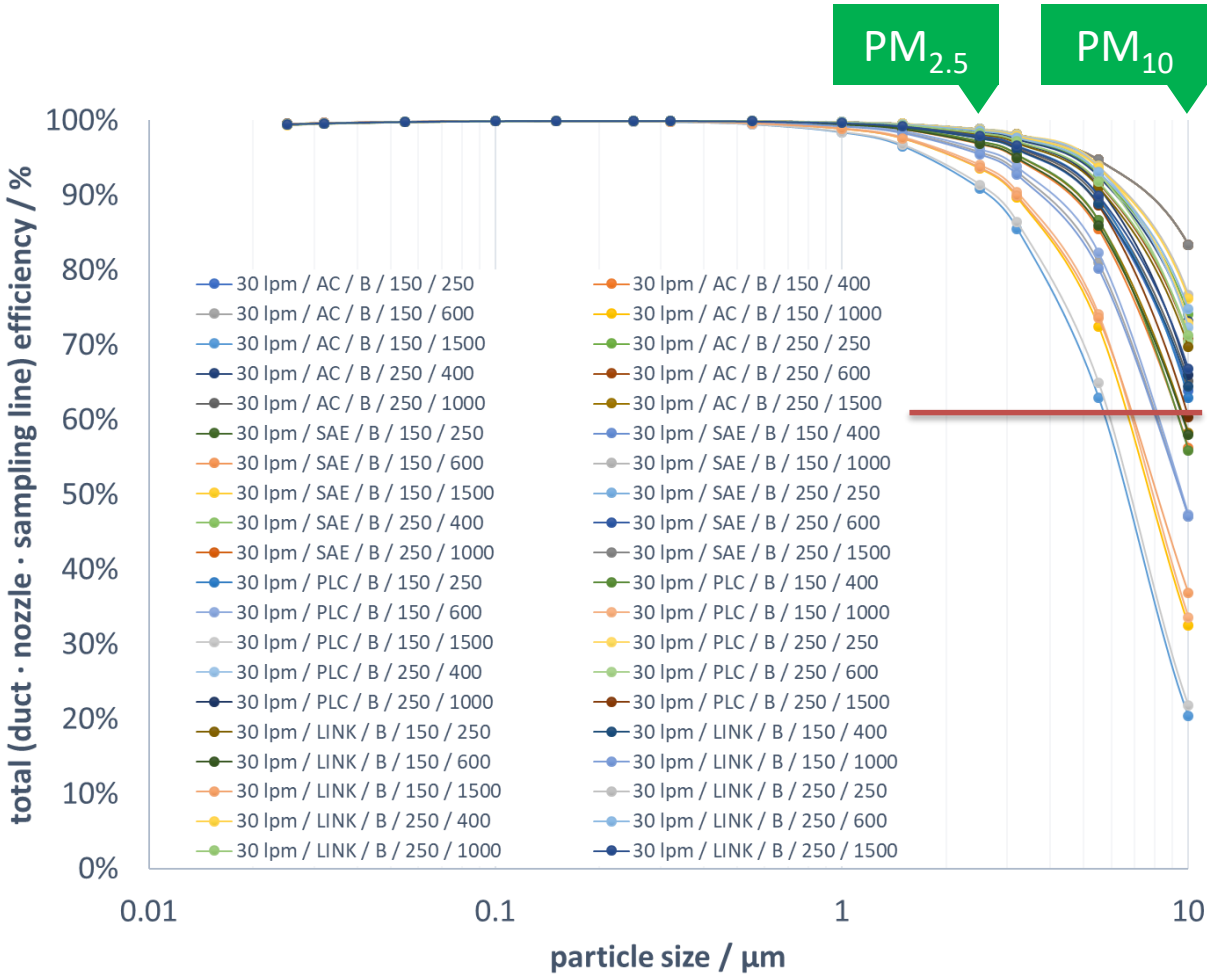
total efficiency for PM at 30 LPM sampling flow

losses in layout A remain above 60% for both duct sizes and all airflows

losses in layout B remain above 60% only for 250-mm duct size in all airflows



Layout A

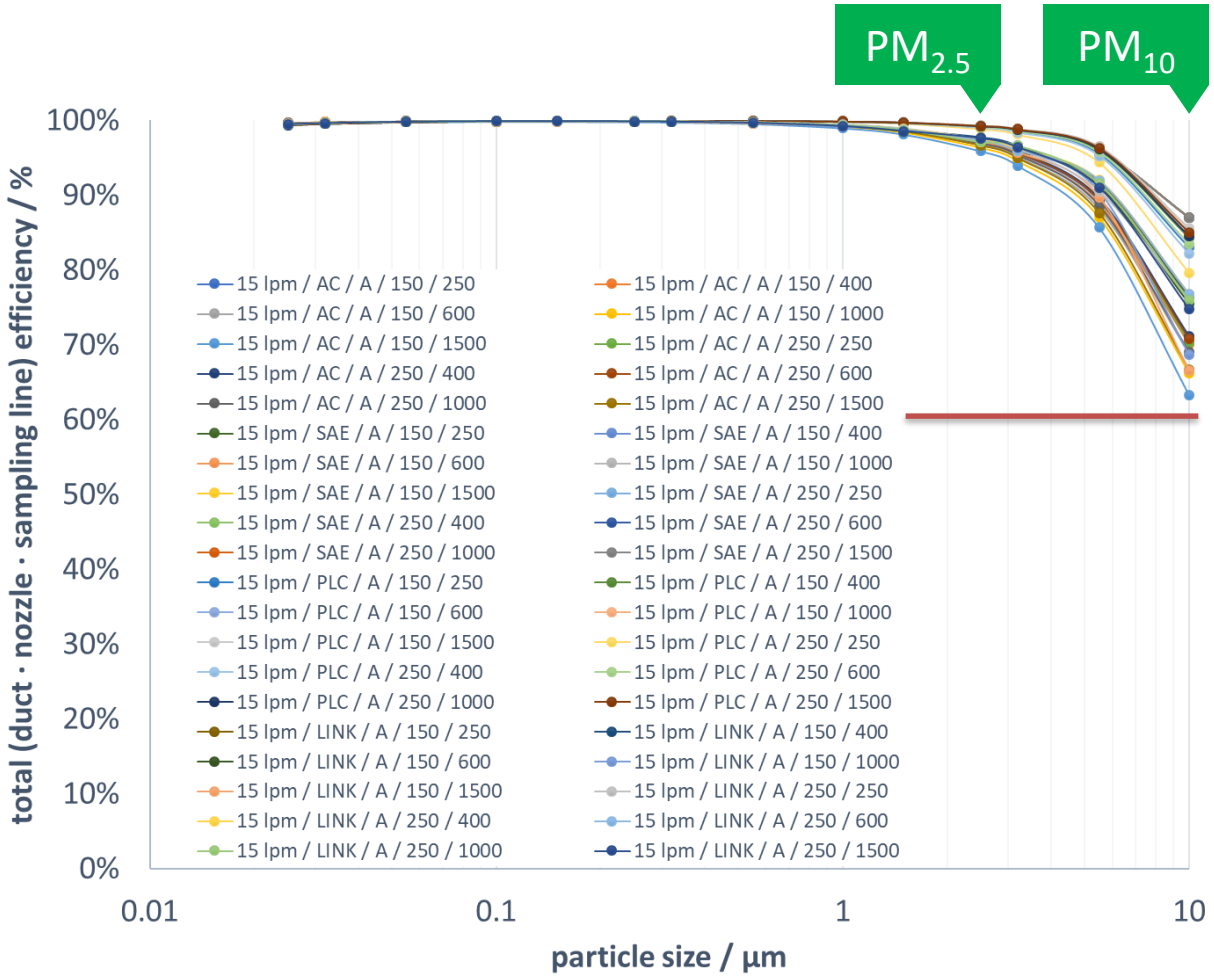


Layout B

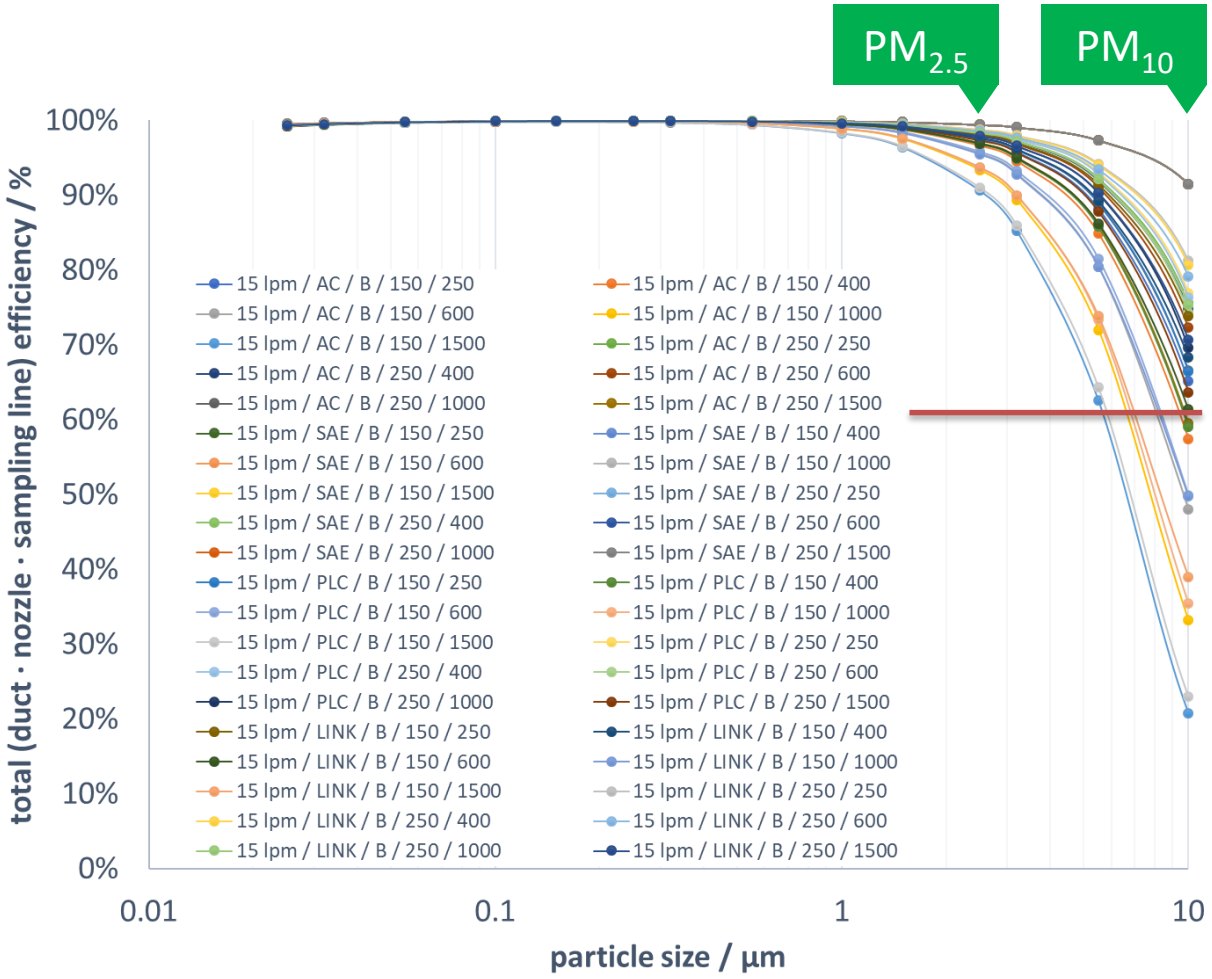
total efficiency for PM at 15 LPM sampling flow

losses in layout A remain above 60% for both duct sizes and all airflows

losses in layout B remain above 60% only for 250-mm duct size in all airflows



Layout A

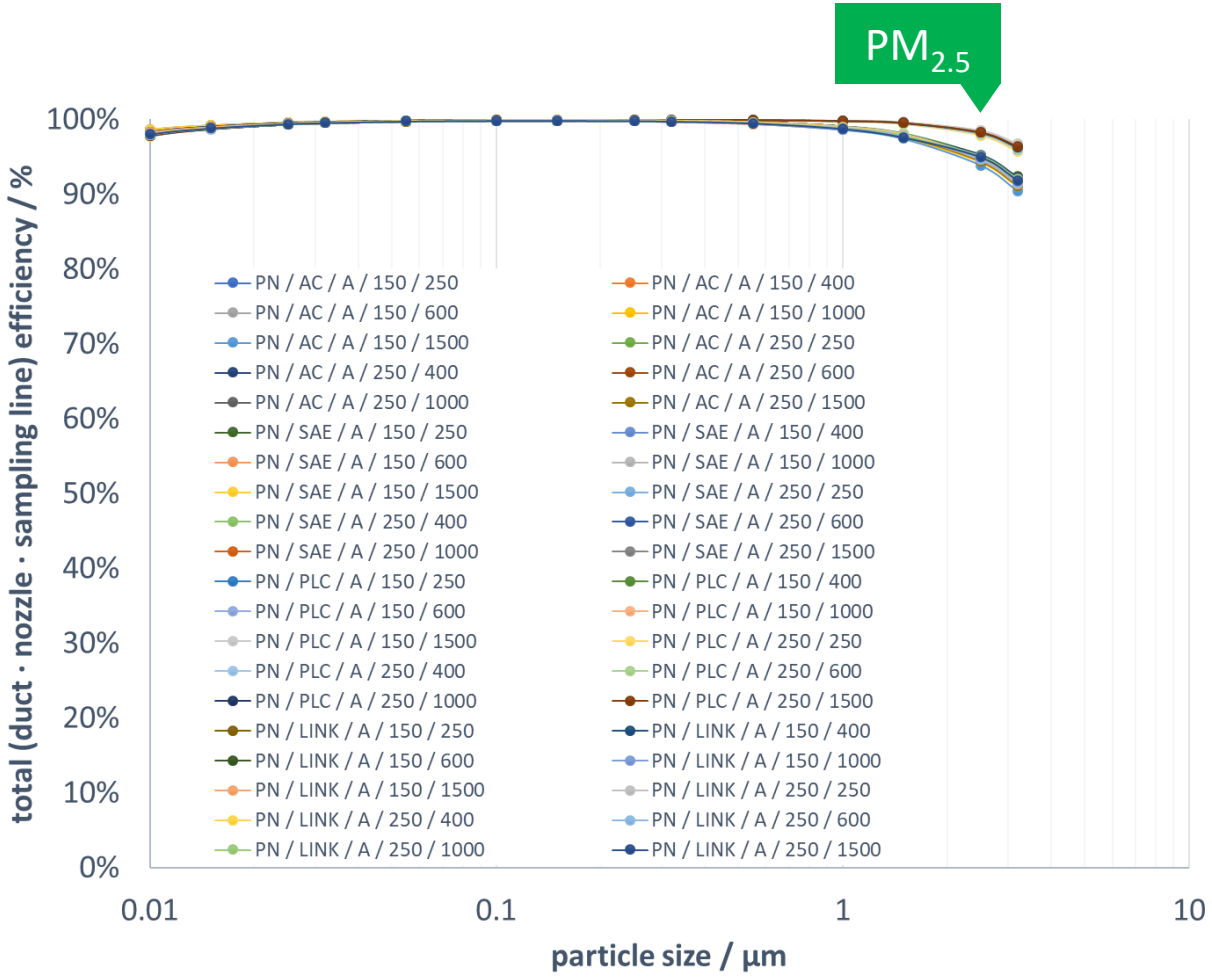


Layout B

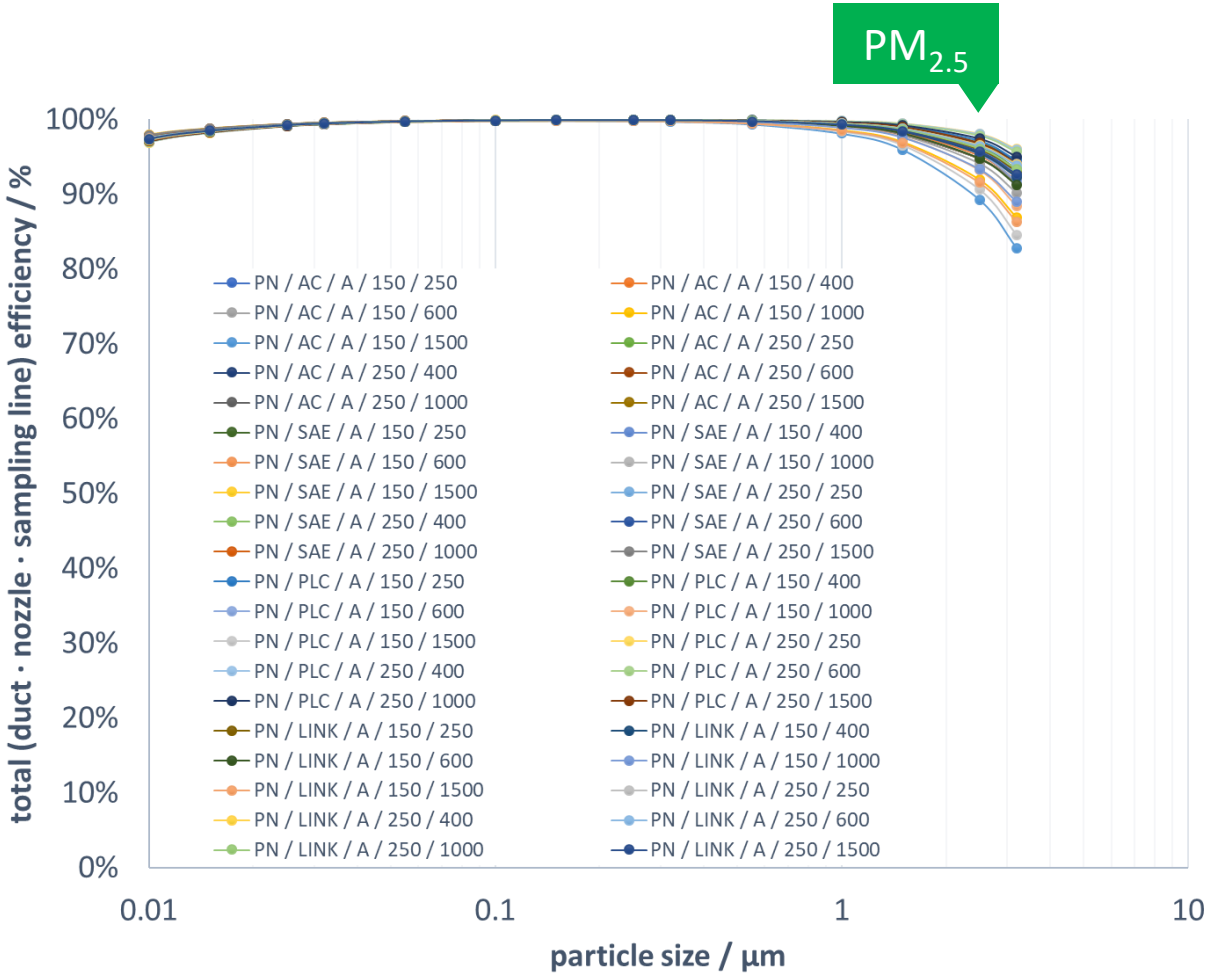
total efficiency for PN at 10 LPM sampling flow

in layout A efficiencies remain above 90% for both duct sizes and all airflows

in layout B efficiencies remain above 80% for both duct sizes and all airflows



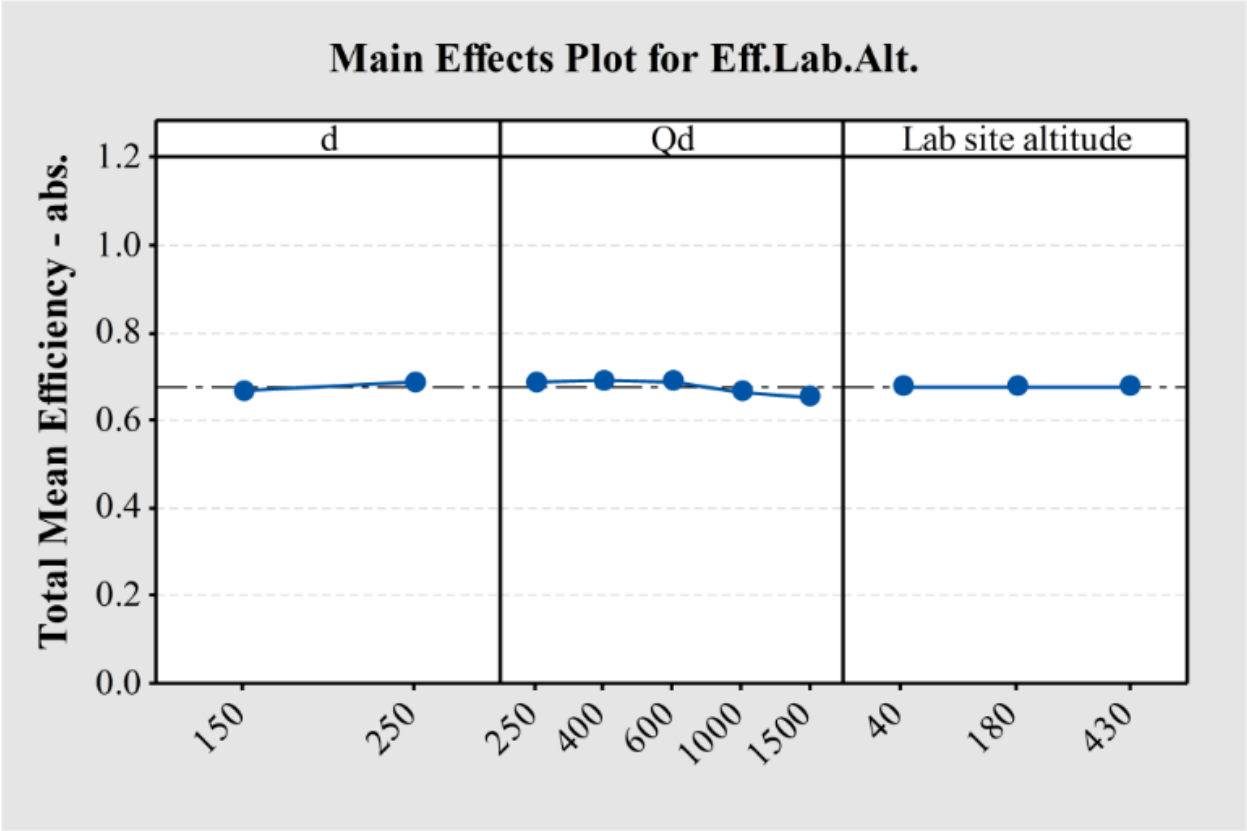
Layout A



Layout B

sensitivity to lab site altitude (above sea level)

e.g.: 150-mm duct and 30 LPM sampling flow for 40 m, 200 m, and 430 m variation in system efficiency is not significantly different among lab location

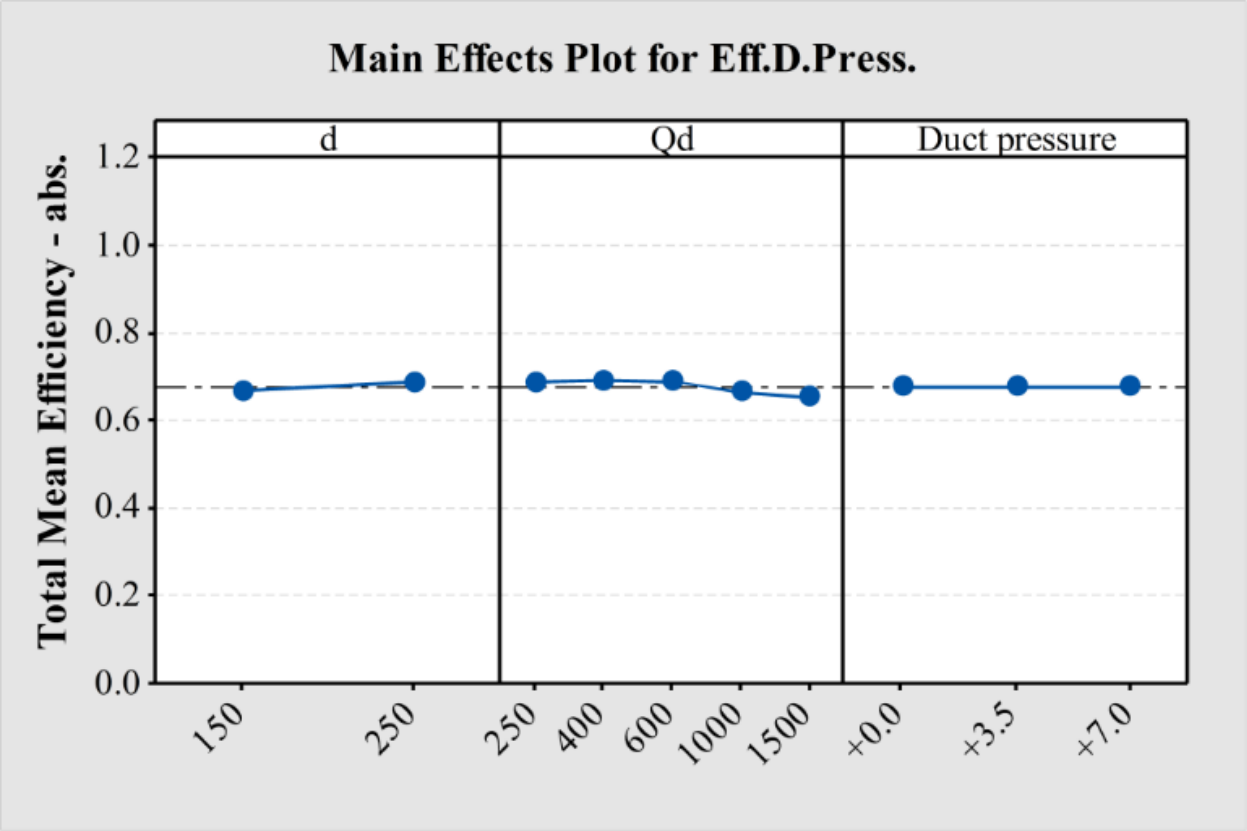


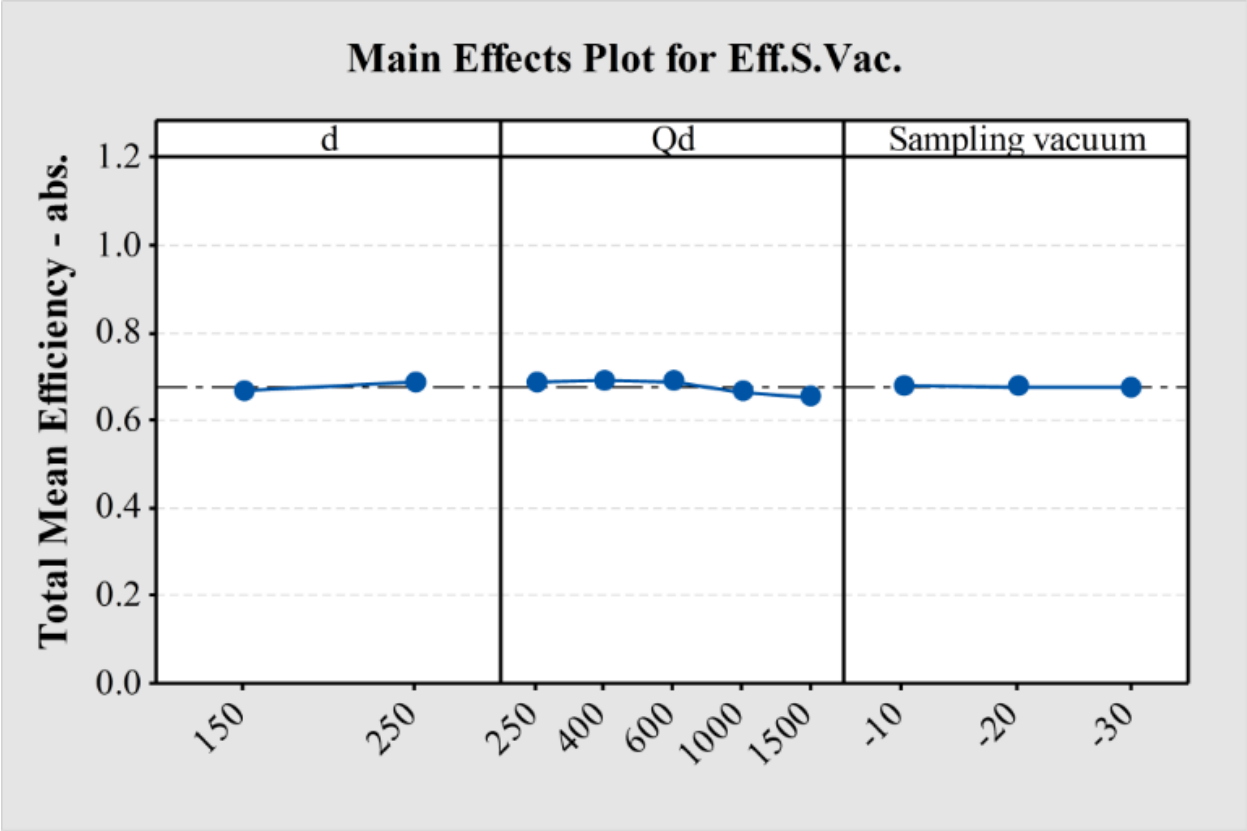
Layout A

sensitivity to transport duct and sampling train air pressure

e.g.: 150-mm duct and 30 LPM sampling flow for layout A only

system efficiency is not significantly different for different duct pressures





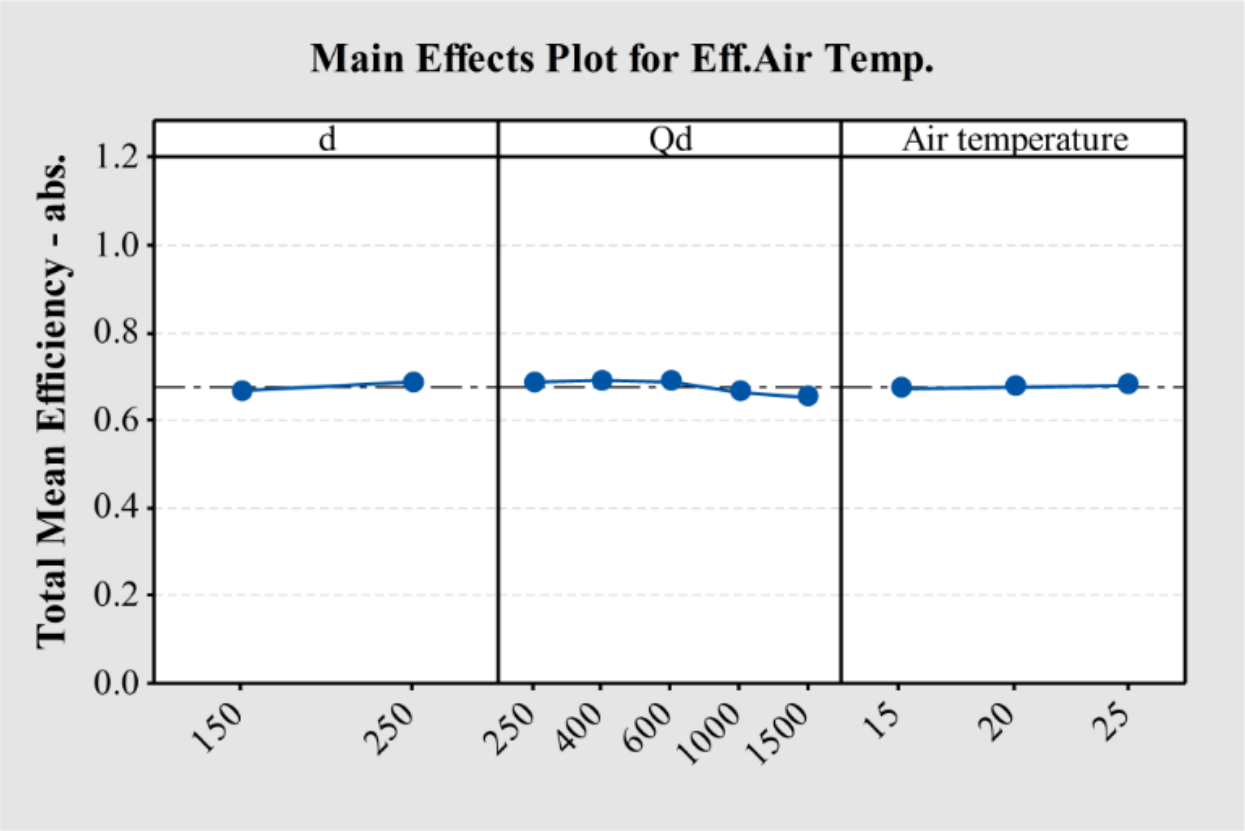
Layout A: duct (+0, +3.5, +7) kPa

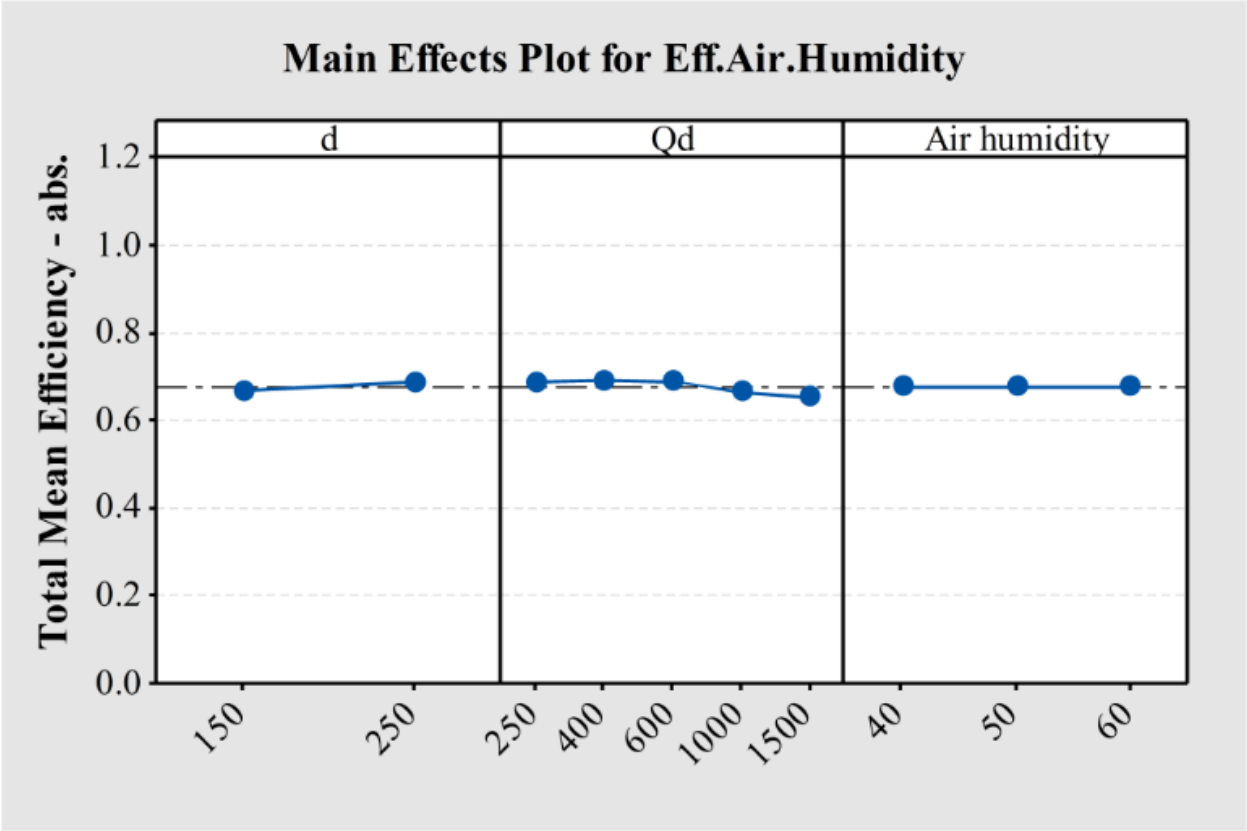
Layout A: sampling (-10, -20, -30) kPa

sensitivity to cooling air environmental conditioning

e.g.: 150-mm duct and 30 LPM sampling flow for layout A only

system efficiency is not significantly different for environmental conditions





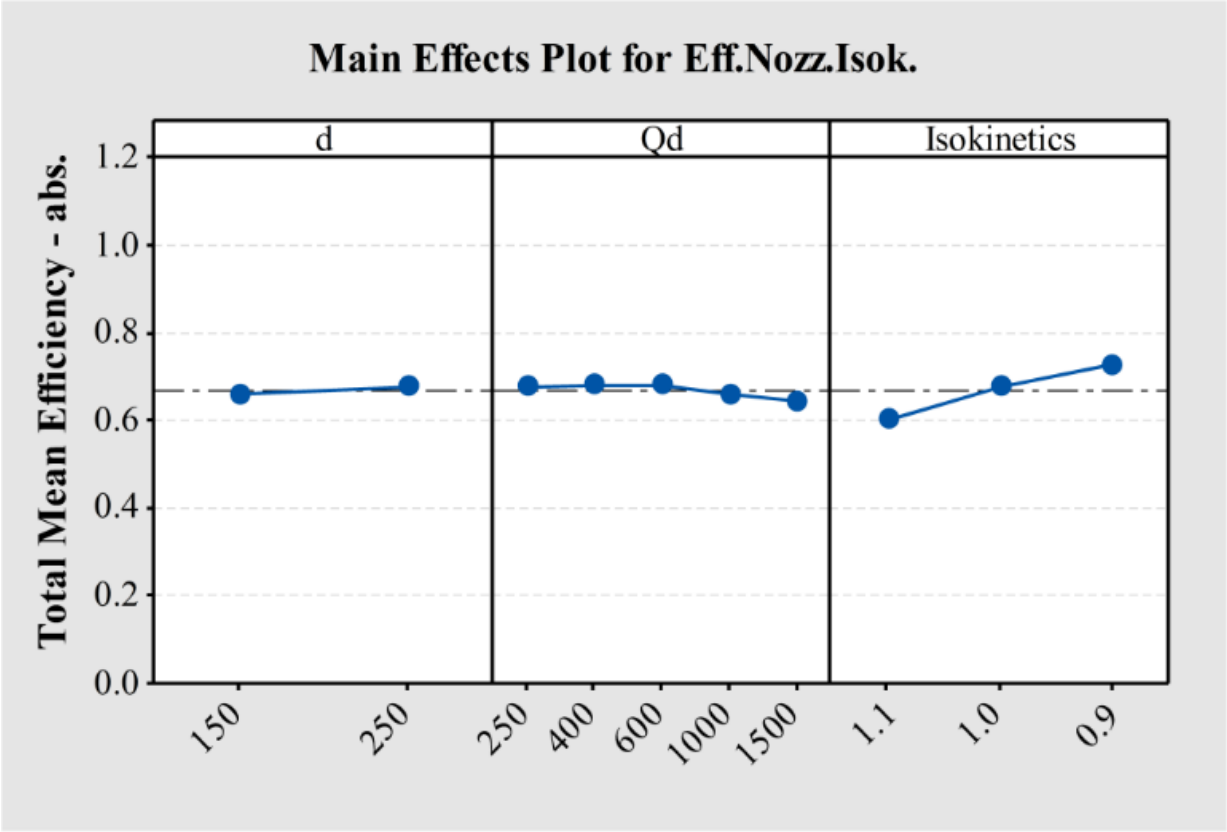
Layout A: temp. (15, 20, 25) °C

Layout A: humidity (40, 50, 60) RH%

sensitivity to isokinetic ratio at sampling nozzle

e.g.: 150-mm duct and 30 LPM sampling flow for three isokinetic ratio

super-isokinetic sampling reduces efficiencies to 70% or less

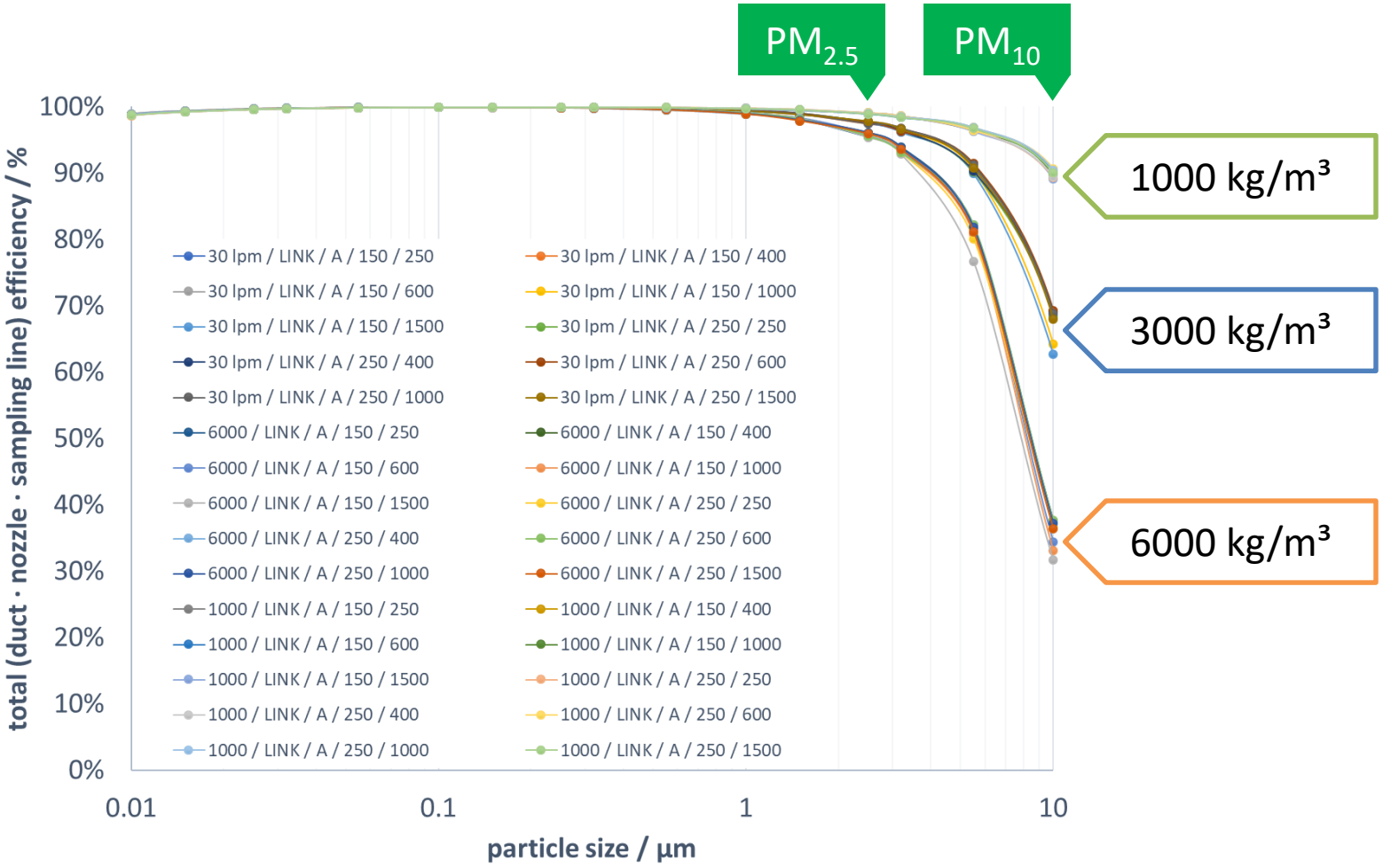


Layout A: isokinetic nozzle (0.9, 1.0, 1.1) ratio (U_s/U_d)

sensitivity to particle density

e.g.: 150-mm duct and 30 LPM sampling flow for different particle densities

heavier particles have a significant influence on (reducing) total efficiency values

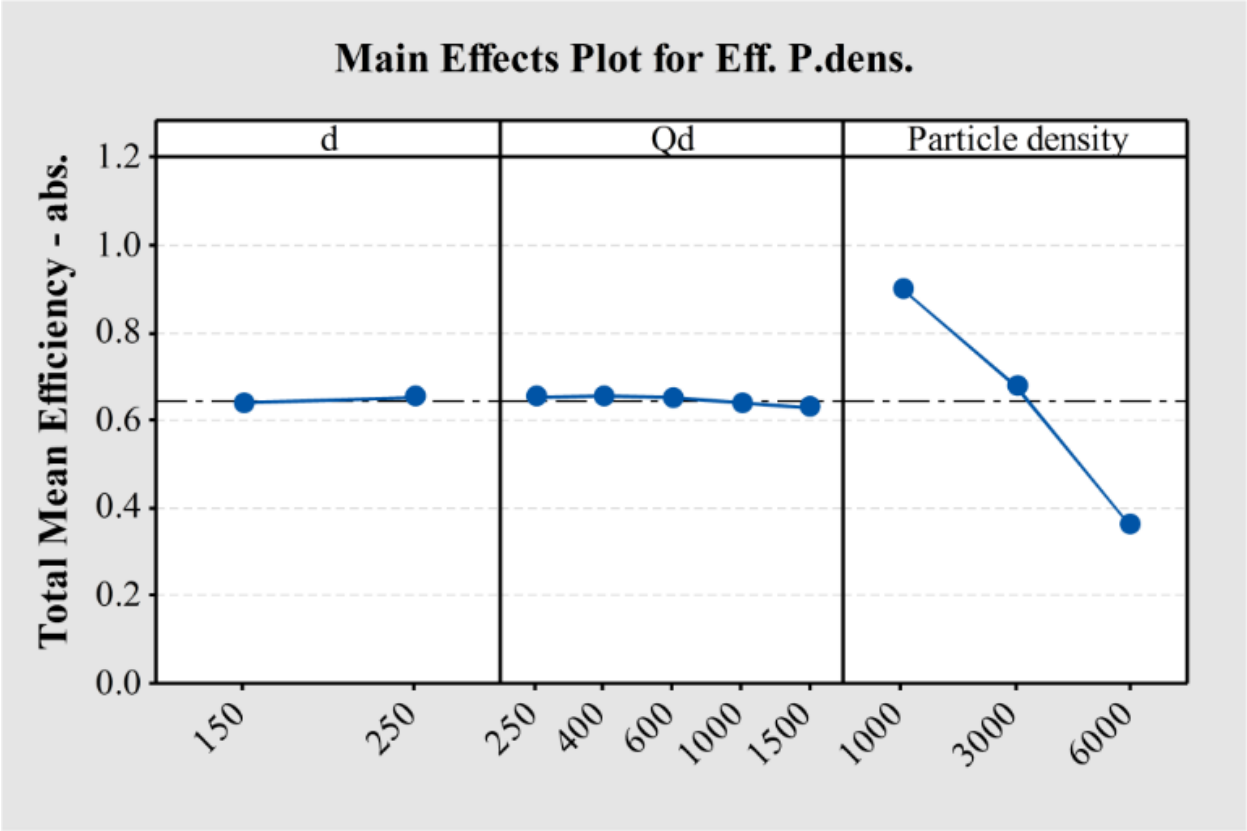


Layout A: particle density (1000, 3000, 6000) kg/m³

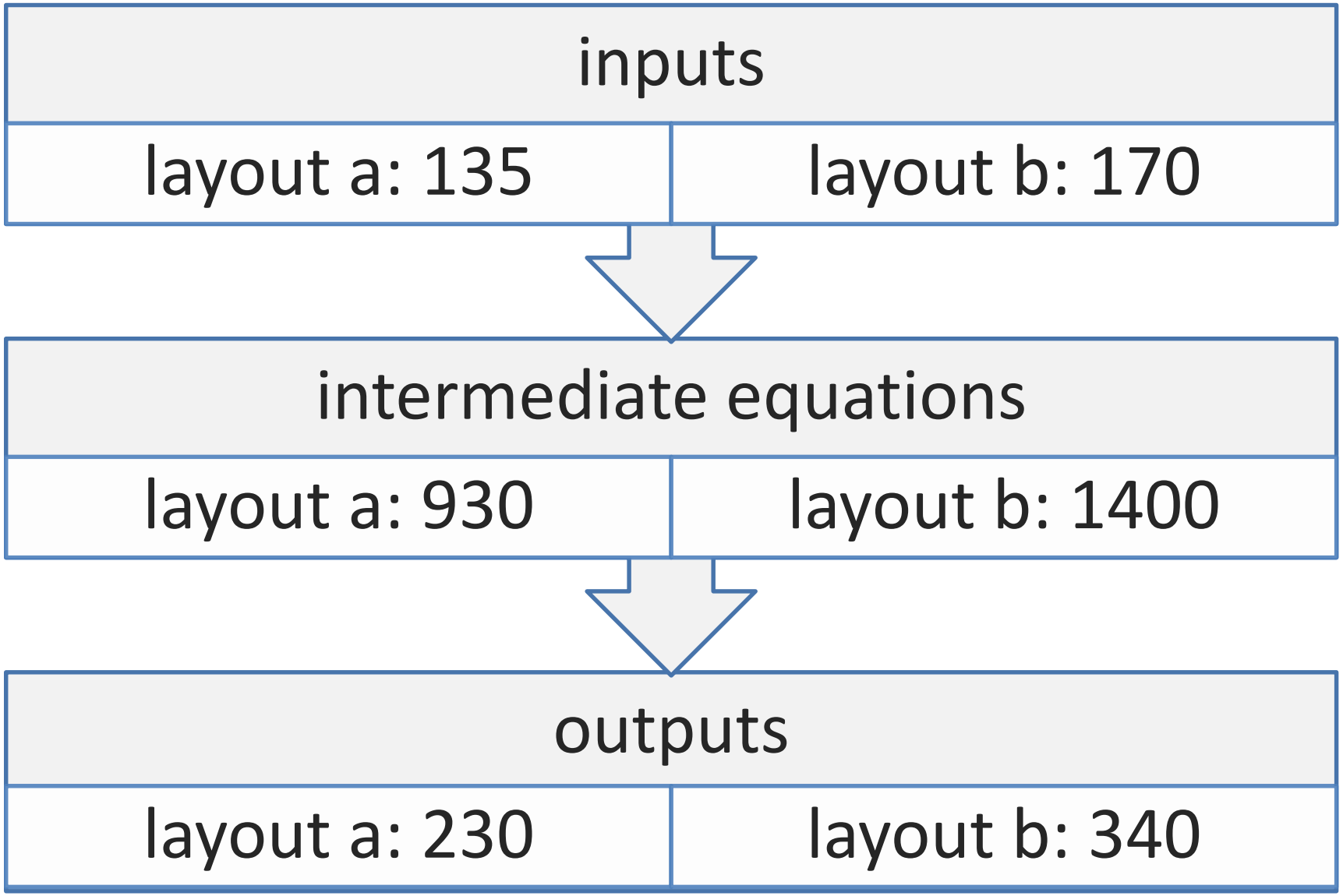
sensitivity to particle density

e.g.: 150-mm duct and 30 LPM sampling flow for different particle densities

heavier particles have a significant influence on (reducing) total efficiency values



Layout A: particle density (1000, 3000, 6000) kg/m³

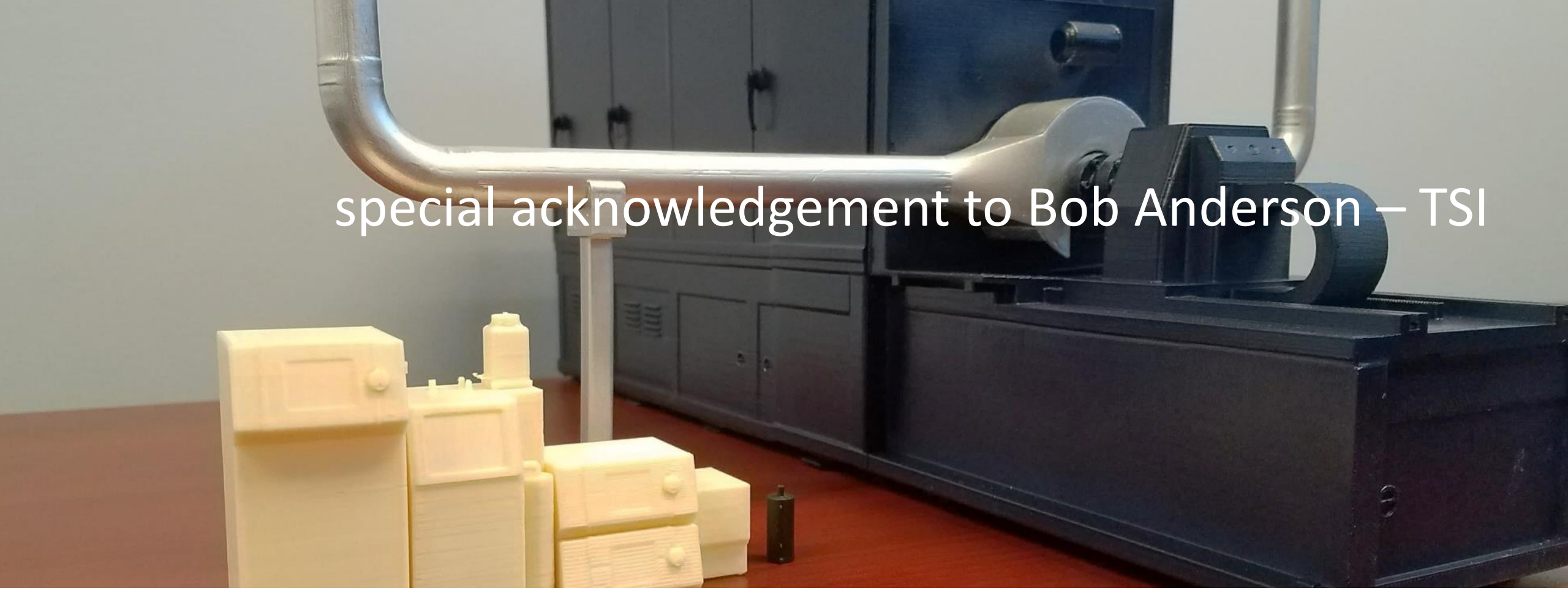

inputs
layout a: 135
layout b: 170
intermediate equations
layout a: 930
layout b: 1400
outputs
layout a: 230
layout b: 340

“Essentially, all models are wrong, but some are useful”

George E.P. Box

“Better be approximately right than exactly wrong”

Carveth Read



special acknowledgement to Bob Anderson – TSI

Carlos Agudelo, Ravi Vedula, and Tyler Odom

47th PMP meting, May 16-17, 2018